PETROLEUM RECOVERY INSTITUTE

# A STUDY OF RHEOLOGY AND FLOW IN POROUS MEDIA OF WATER-IN-HEAVY OIL EMULSIONS

(PART OF ENERGY, MINES AND RESOURCES COST-SHARED ENERGY CONVERSION PROGRAM AND PART OF THE PROGRAM OF THE FEDERAL PANEL ON ENERGY R & D (PERD))

FINAL REPORT

BY

ROY WOO, CLIVE JACKSON AND BRIJ MAINI

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## SUMMARY

This report presents the results of an experimental investigation of the effects of a chemical additive on rheology and flow in porous media of water-in-heavy oil emulsions. Two heavy oil systems were evaluated: the first was from a field being produced under primary production, the other from a field that was produced under fire flood. A commercially available surfactant (Chevron Chaser CS1010) was used as the additive.

The effect of this additive on emulsion rheology was evaluated by measuring the shear stress vs shear rate curves with a Couette flow rheometer. Measurements were carried out at four different temperatures with and without the chemical additive. The effect of the additive on drop size distribution was also measured.

An apparatus for investigating the flow behaviour of water-in-oil emulsions was designed and fabricated. A micro-wave attenuation technique was developed to measure the in-situ saturation of free water. Flow experiments were conducted at four different temperatures. The flow tests involved measuring the pressure drop across a sand pack at different flow rates. In addition to the pressure drop, changes in the free water saturation with time at a fixed point in the sand pack were monitored by the micro-wave technique. Changes in the drop size distribution and the volume fraction of emulsified water resulting from the flow through the sand pack were measured.

It was found that in the presence of Chevron Chaser CS1010 the pressure drop across the sand pack was up to 50% smaller compared to the pressure drop in the additive free system at the same flow rate. In addition, in most cases the emulsion samples collected at the sand pack outlet showed a greater reduction in the volume fraction of emulsified water in presence of the additive.

The exact mechanism of the flow enhancement provided by the additive could not be established. It appeared to be a reduction in the interfacial viscosity of the oil/water interface.

## SOMMAIRE

Ce rapport présente les résultats d'une étude expérimentale sur les effects qu'un additif chimique peut avoir sur la rhéologie et l'écoulement en milieu poreux d'une émulsion d'eau-en-huile lourde. Pour se faire, deux systèmes d'huile lourdes furent évalués: le premier provenant d'un gisement pétrolifère produit en régime primaire, l'autre provenant d'un gisement qui était produit en utilisant la récupération assistée par la combustion souteraine. Un surfactant commercial (Chevron Chaser CS1010) fut utilisé comme additif. Aussi, l'effect de l'additif sur la distribution des dimensions de gouttes a été mesuré.

L'effect de cet additif sur la rhéologie de l'émulsion fut évalué en mesurant les efforts de cisaillement contre le taux de cisaillement obtenus, à l'aide d'un rhéomètre Couette. Les données furent obtenues pour quatre températures différentes pour des systèmes avec ou sans additif chimique.

Pour investiger le comportement de l'écoulement d'une émulsion eau-huile on a du développer un appareil spécifique à cet application. Une technique d'atténuation des micro-ondes fut développée afin de mesurer la saturation in-situ de l'eau libre. Les essais d'écoulement furent conduits à quatre températures différentes. Les essais consistaient à mesurer la pression différentielle le long d'un milieu poreux, et cela à quatre débits différents. En plus de la pression différentielle, on mesura, à l'aide de la technique micro-onde, les changements de saturation d'eau libre en fonction du temps et ce pour un point fixe du milieu poreux. On a pu mesurer les changements dans la distribution et la grosseure des gouttes ainsi que la fraction de volume d'eau émulsifiée résultant de leur passage par le milieu poreux.

Ainsi l'on trouva qu'en présence du Chevron Chaser CS1010, la pression différentielle du milieu poreux était jusqu'à cinquante pourcent plus petite que la pression différentielle le long des systèmes qui n'avaient aucun additif. De plus, grace aux échantillons recueillis à la sortie du milieu poreux, on constata une plus grande réduction de la fraction de volume d'eau émulsifiée.

Les méchanismes responsables de la réduction de la pression différentielle causée par l'additif, nous échappent encore pour le moment. Cependant, il semble que ce soit causé par une réduction de la viscosité d'interface de la phase huile/eau.

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# SUMMARY

This report presents the results of an experimental investigation of the effects of a chemical additive on rheology and flow in porous media of water-in-heavy oil emulsions. Two heavy oil systems were evaluated: the first was from a field being produced under primary production, the other from a field that was produced under fire flood. A commercially available surfactant (Chevron Chaser CS1010) was used as the additive.

The effect of this additive on emulsion rheology was evaluated by measuring the shear stress vs shear rate curves with a Couette flow rheometer. Measurements were carried out at four different temperatures with and without the chemical additive. The effect of the additive on drop size distribution was also measured.

An apparatus for investigating the flow behaviour of water-in-oil emulsions was designed and fabricated. A micro-wave attenuation technique was developed to measure the in-situ saturation of free water. Flow experiments were conducted at four different temperatures. The flow tests involved measuring the pressure drop across a sand pack at different flow rates. In addition to the pressure drop, changes in the free water saturation with time at a fixed point in the sand pack were monitored by the micro-wave technique. Changes in the drop size distribution and the volume fraction of emulsified water resulting from the flow through the sand pack were measured.

It was found that in the presence of Chevron Chaser CS1010 the pressure drop across the sand pack was up to 50% smaller compared to the pressure drop in the additive free system at the same flow rate. In addition, in most cases the emulsion samples collected at the sand pack outlet showed a greater reduction in the volume fraction of emulsified water in presence of the additive.

The exact mechanism of the flow enhancement provided by the additive could not be established. It appeared to be a reduction in the interfacial viscosity of the oil/water interface.

# INTRODUCTION

From the viewpoint of a heavy oil producer the frequently encountered water-in-oil emulsions are just a big nuisance. From very early days he has been trying to develop ways of killing the produced emulsions. He knows that the oil can not be sold without removing the emulsified water. The cost of de-emulsification reduces his profits. What he did not know till recently is that these emulsions may be costing him more even before being produced from the well, by decreasing the flow of oil into the production well. While it has been claimed that emulsions are produced when the constituents move through valves and other flow constrictions which produce high shear stress, it is also known both from theoretical and experimental considerations that emulsions can be formed in the reservoir[1].

Most heavy oil reservoirs are produced by some reservoir stimulating method such as water, steam, or fire flood. The stimulated production of heavy oil can subject the flowing oil-water mixture to fairly high shear rates, particularly in the near-well bore region. This can provide sufficient energy for creation of water-in-oil emulsions unless the interfacial chemistry too strongly resists forming such emulsions. The impact of such emulsion creation on oil production rate will depend on the nature of the emulsions produced. It is also self evident that by altering the interfacial chemistry we may be able to suppress emulsion formation or change the flow behaviour of formed emulsions in a favourable direction. It can be seen, therefore, that an understanding of emulsion stability and flow of water-in-oil emulsions through porous media is important to oil recovery.

The flow of water-in-heavy oil emulsions in porous media has received very little attention in the literature. Basic mechanisms involved in the flow have not been investigated. The effects of reservoir parameters, such as permeability, wettability, type of crude and gas-oil-water ratios are not known. Therefore, it is extremely difficult to formulate chemical additives for modifying the emulsion flow behaviour. However, several vendors of oil field chemicals have recently started marketing chemicals which are purported to improve heavy oil recovery by reducing the apparent viscosity of water-in-heavy oil emulsions.

These claims have not been confirmed by any published laboratory studies. Secondly, even if these surfactants do reduce the apparent viscosity as measured by a viscometer, this may or may not translate to improved production potential. It is therefore essential to develop techniques for assessing the performance of such chemicals by studying their effects on flow of emulsions through porous media. More importantly, it is apparent that a need exists to develop a vastly improved understanding of the physics of water-in-oil emulsion flow in porous media.

Emulsion theory has been developed in the fields of chemistry and physics where the components used are either pure or known. Moreover, the components are usually chosen so that the viscosity does not cause any major problems during emulsion stability analysis or during emulsification. However, little experimental information exists for complex crude oil systems.

It has been recognized that drop size and drop size distribution affect emulsion behaviour in many ways. In particular, researchers observed that the dispersed phase starts to have a pronounced influence on the emulsion rheology at lower concentrations as the drop size becomes smaller [2]. Consequently, a plot of apparent viscosity as a function of mean particle diameter would not represent the influence of drops with sizes less than the mean diameter. That is, both the particle size and the particle size distribution must be considered if theoretical predictions that fit experimental results are to be developed [3].

It has been stated that oilfield emulsions are primarily stabilized by highly rigid films that are formed at the oil-water interfaces by polar asphaltene and resin fractions [4,5,6]. The adsorption of fine solids from the crude oil such as precipitated waxes and formation solids act to further stabilize these emulsions. The physical characteristics of such interfacial films are a function of crude oil type and solids content, the aqueous phase pH and ionic composition, temperature, age of the interface, extent to which the adsorbed film is compressed, and concentration of polar molecules in the crude oil phase. These interfacial films act strictly as mechanical barriers to coalescence of droplets and hence the emulsion stability is enhanced.

One of the factors which influences the properties of interfacial films is temperature. The temperature will influence the rate of build-up of interfacial films by changes in the adsorption rate and character at oil-water interfaces. It will also affect the film compressibility by changing the solubility of the

natural surfactants of the crude oil in the bulk phases, and it will also affect emulsion rearrangement processes[4]. Changes in temperature also affect the emulsion stability and rheology by increasing the interaction/collision rate through Brownian motion and by changing the vapour pressure and viscosity of liquid constituents[7].

Studies of water-in-heavy oil emulsions have found that the rheology of the emulsion is relatively Newtonian at low shear rates, but as the shear rate is increased, the rheological behaviour becomes pseudoplastic (shear-thinning) and as the shear rate is further increased, becomes Newtonian again[8,10]. The amount of viscosity reduction has been shown to be a function of water concentration and the type of surfactant. This type of behaviour has been attributed to several reasons. First, the growth of droplet aggregates could occur at low shear rates and the disruption of these aggregates could occur at high shear rates [2,7,8]. Second, water droplets deform into a film which allows slippage of part of the viscous fluid relative to an adjoining part[8,10]. Third, in systems in which the water content is high, a phase inversion which is dependent on the degree of agitation, may take place[8,11].

In this report we present the results of an experimental study which was undertaken to show the feasibility of altering the in-situ emulsion behaviour with injected surfactants. Two heavy oil systems were evaluated: the first was from a field being produced under primary production, the other from a field that was produced under fire flood. A commercially available surfactant (Chevron Chaser CS1010) was used as the additive.

# OBJECTIVES

The main objective of this work was to show the feasibility of improving the in-situ emulsion behaviour with chemical additives. The specific aims were as follows:

1. To investigate the effect of Chevron CS1010 on the rheological properties of water-in-heavy oil emulsions.
2. To develop an apparatus for studying the flow of water-in-heavy oil emulsions in porous media.
3. To investigate the flow behaviour of water-in- heavy oil emulsions in porous media.
4. To evaluate the effects of Chevron CS1010 on flow of water-in-heavy oil emulsions in porous media.

# MATERIALS AND METHODS

## MATERIALS:

### CHEVRON CHASER CS1010:

This surfactant is a proprietary chemical marketed by Chevron Chemical Company as a cyclic steam additive. It was provided as a research sample in form of a 50 wt% active component solution in water.

### PRODUCED WATER-IN-OIL EMULSION FROM WOLF LAKE:

This wellhead sample from a reservoir which was being fire-flooded was supplied by BP Canada. The as received material contained substantial amount of suspended solids. In order to remove the particulate matter, the emulsion was cleaned and reconstituted using the methodology to be discussed later.

### PRODUCED WATER-IN-OIL EMULSION FROM LINDBERGH:

This well head sample from a reservoir under primary production was supplied by Pan Canadian Petroleum Limited. This emulsion was also cleaned to remove suspended solids.

## PREPARATION OF EMULSION SAMPLES:

In order to remove the suspended solids and control the uniformity of the starting materials, the wellhead oil samples were first separated from entrained water and solids, then the separated oil and water were recombined in a controlled fashion to produce emulsions whose water contents were the same as those prior to the separation.

This separation of the wellhead samples was accomplished by centrifugation at 10,000 RPM for one hour (in the case of the Pan Canadian sample) or by solvent extraction using methylene chloride (in the case of the Wolf Lake sample). Solvent extraction was necessary in the cleaning of the Wolf Lake sample because the water and oil densities were very similar, making separation by centrifugation unfeasible. It is important to note that gas chromatography-mass spectroscopy of the processed Wolf Lake oil showed no detectable residual solvent. The solids removal was necessary to protect the rheometer and pumping equipment from possible damage. The suspended solids can also make the analysis and interpretation of the results more difficult by causing core plugging during the flow experiments. Although, the solids may actually play an important role in stabilizing the in-situ emulsions, in this study we considered it wise to avoid the complications they would have caused in experiments and interpretation of the results.

The separated oils and waters were then split into two batches prior to recombination. To one batch of each water sample was added enough Chevron CS1010 cyclic steam surfactant to produce the manufacturer's recommended final bulk active concentration of 0.05 wt%. The batches were then reconstituted using a flow-through high shear homogenizer. The mean drop size of the emulsions produced by this method was smaller than the mean drop size in the original emulsion. Thus, from this procedure, four batches of emulsions were produced: two Pan Canadian emulsions (one of which contained 0.05 wt% CS1010), whose final water concentration was 31.53 wt%, and two Wolf Lake emulsions (one of which contained 0.05 wt% CS1010) whose final water concentration was 18.96 wt%. The direct addition of the cyclic steam surfactant into the formation water poses no ideological objections, since in field applications, the chemical is normally added directly into the injection steam and so enters the reservoir in an aqueous phase.

These reconstituted emulsions were further split into two batches: one batch for storage and another for flow experiments. The flow batches were then poured into individual bottles that were kept frozen until used. The freezing was considered necessary to preserve the drop size distribution of the emulsions and reduce the chances of other changes in the emulsion characteristics by chemical or microbial reactions. It should be mentioned that freezing of water-in-heavy oil emulsions does not have the same type

of emulsion breaking effect as freezing of oil-in-water emulsions or water-in-low viscosity oil type emulsions. We have found that in these emulsions the continuous phase viscosity increases rapidly as the emulsion temperature decreases whereby immobilizing the water droplets before they are frozen. Therefore, the emulsion droplets freeze separately and there is little or no damage to the emulsion structure. During the thawing at room temperature the frozen water droplets melt while the oil viscosity is still very high. The samples used for evaluating the effect of storage at room temperature were left in bottles that were kept at room temperature for the duration of the study.

## APPARATUS FOR EMULSION FLOW EXPERIMENTS:

Flow of water-in-heavy oil emulsions through porous media is a complex process involving several mechanisms associated with two phase flow including relative permeability and wettability effects. In addition there is the added complexity of non-Newtonian fluid properties and the likelihood of changes in droplet size distribution and filtration of the emulsified water. The equipment for an experimental study of this complex flow process must, therefore, meet several requirements. These include provisions for measuring in-situ water saturation along with pressure drop across the porous media at high overall pressures and temperatures. Of course, the apparatus must also have provisions for collecting the produced emulsions without further altering the emulsion properties.

To that end, the equipment detailed schematically in Fig. 1a was developed. The operation of the apparatus is straightforward. Water is used as a hydraulic fluid to displace the emulsion sample initially present in the upstream piston transfer vessel through the core which is housed in an oven. The produced emulsion is captured by a similar piston transfer vessel on the exit side of the apparatus. The use of transfer vessels in this manner eliminates the possibility of further altering emulsion properties. Also, a minimum system pressure of 100 psig was maintained on the whole flow system during all tests through the use of the back-pressure regulator at the exit to the system.

The core used at all temperatures except 150 C was a sandpack 21cm long, 1.9cm wide, and 0.64cm deep having a pore volume of 8.93ml (33.9% porosity), and a permeability to water of 8.53 darcy.

The core used at 150 C was a sandpack 21.6cm long, 1.9cm wide, and 2.54cm deep having a pore volume of 41.02ml (35.4% porosity), and a permeability to water of 11.2 darcy. This core, alone, greatly attenuated the microwave beam used to obtain point saturation measurements and because the structural integrity of the other core would be compromised at 150 C, no saturation measurements were obtained for that temperature.

The in-situ water saturation measurement was achieved through microwave attenuation. The microwave schematic of the flow apparatus appears in Fig. 1b. The operation of this part of the apparatus is quite simple. A microwave source produces a beam of microwave radiation which gets split at a beam splitter. The reference portion of the beam travels immediately to a power sensor. The test beam continues on through the core after first passing through a microwave isolator. The isolator prevents reflective interference from affecting either the reference beam or the microwave source. The reacted beam is then caught by the receiving horn and the beam passes on to another power sensor. The power sensors convert the microwave beams into low frequency AC power. These power signals are then sent to a power meter in which they are compared. The processed signal represents the microwave attenuation and therefore, the water saturation at the point.

The use of microwaves for the measurement of moisture in porous media has been known and used for many years (13-15). Microwave radiation is strongly absorbed by water, but is virtually unattenuated by nonpolar materials. The frequency used in this study was 33.5 GHz. At this frequency, the horn-lens arrangement across the core could focus the beam to an area of approximately 2.1cm by 2.8cm. The focal area was located one third the core length from the emulsion entry port.

During the development of this apparatus, it was found that the attenuation was quite weak when the material under examination was pure emulsion with no bulk phase water. This was due to the poor electromagnetic coupling between the very small drops of water and the relatively very large microwave wavelength. However, when a bulk phase of water was introduced, the microwave attenuation increased sharply. Thus, it was found that the attenuation was a linear function of bulk phase water, substantially unaffected by the presence of emulsified water.

The system was calibrated with clean formation water and anhydrous oil for each of the systems under investigation. Since microwave attenuation in water varies with temperature and salinity, the flow cell was recalibrated for each system at each of the experimental temperatures.

## MEASUREMENT OF RHEOLOGY:

The rheological behaviour of emulsions was determined through the use of the Contraves Rheomat 30 rheometer in conjunction with two measuring heads. One head was a magnetically coupled enclosed system suitable for use at high temperature and pressure but required about 110 ml of sample. The other head was an open cup system and was suitable for use at lower temperatures and atmospheric pressure but required only 20 ml of sample. Both heads were of the concentric cylinder type. Conical end sections on the measuring heads reduced end effects on the measurements.

The high pressure and temperature measuring head was used to measure all the storage sample rheologies as well as to measure the rheologies of any sample at a temperature of 100 C or higher. The low pressure and temperature measuring head was used at the other times.

## MEASUREMENT OF DROP SIZE DISTRIBUTION:

The measurement of drop size distribution proved to be a difficult task. Because of the totally opaque, highly viscous and electrically non-conducting nature of the continuous phase these emulsions are not amenable to drop size measurements by light scattering, light diffraction or electozone methods. The only practical technique appears to be the direct visual examination under a microscope. Although it is an extremely tedious method and is not totally free of artifacts, in absence of a better alternative, this was the technique used. A small drop of the emulsion was sandwiched between to thin glass slides. Photomicrographs were taken of the sandwiched droplet. The image of the negative was then projected onto a large screen. Approximately 100 randomly chosen droplets were then selected and measured. Next, the compiled measurements were sorted according to size and counted. Histograms were finally made based on this data.

## DETERMINATION OF BULK EMULSION WATER CONTENT:

The fraction of water in emulsion samples was determined by Karl-Fischer titration. In case of emulsions produced from the sand pack in flow experiments the water produced as a separate bulk phase was removed before the titration.

## CORE PACKING:

The core material used throughout this study consisted of water washed silica sand of a size between 115 mesh and 110 mesh (U.S. Standard). In the actual packing process, small volumes of dry sand was dropped into the dry core holder under gentle vibration. Periodical tapping of the core holder during the packing process aided in the filling process.

## TEST PROCEDURES:

### A. For measuring the effect of Chevron CS1010 on the rheological properties of water-in-heavy oil emulsions:

The two heavy oil systems were treated as described previously in the preparation of emulsions section to produce four batches of emulsions: one each of the untreated heavy oil systems and one each of the heavy oil systems containing Chevron CS1010. On an approximately monthly basis, samples of the emulsions were tested for their rheology and droplet size distributions. The rheological measurements were run at four different temperatures: 23 C, 50 C, 100 C, and 150 C.

### B. For the flow behaviour of water-in-heavy oil emulsions in porous media.

The emulsion samples prepared as described previously and individually bottled and frozen were thawed 12 hours prior to use to allow any air bubbles to be released. The sample was then loaded into the transfer vessel and all flow lines leading to the flow cell was then filled with the sample. A data acquisition

program was used to gather data from the experiment at periodic intervals.

The flow sequence for all the flow experiments with the exception of room temperature Wolf Lake runs are as follows:

1. The core was cleaned of the previous material by washing with the solvent sequence: toluene, isopropanol, water, isopropanol.
2. The core was dried and then evacuated by a vacuum pump.
3. The formation water for the particular test was allowed to fill the pore volume of the core.
4. The emulsion with no surfactant was passed through the core and measurements were taken.
5. The emulsion with surfactant was passed through the core and measurements were taken. In the case of the room temperature Wolf Lake regular run, the core was taken to residual water saturation with anhydrous Wolf Lake oil before the emulsion flow experiment began. Then, the core was cleaned, evacuated, and filled with formation water before the Wolf Lake emulsion with CS1010 flow experiment began.

The measurements consisted of differential core pressure, point water saturation, and core temperature during the experiment. Measurements on the produced emulsion consisted of emulsion rheology, droplet size distribution, and emulsion water content. Usually, three flow rates were used for each emulsion.

# RESULTS:

## NOMENCLATURE:

For the purposes of this report, the emulsions are referred to by the following notation:

PCR - PAN CANADIAN EMULSION, REGULAR (no CS1010)

PCC - PAN CANADIAN EMULSION, WITH CS1010

WLR - WOLF LAKE EMULSION, REGULAR ( no CS1010)

WLC - WOLF LAKE EMULSION, WITH CS1010

In cases in which numbers follow the identifier, the first number refers to the temperature of the experiment. For emulsions produced at the core outlet in flow experiments a second number follows a dash and refers to the flow rate used (in ml/min). For example, WLC100-.2 refers to Wolf Lake emulsion with CS1010 after flowing through the sand core at 100 C and 0.2 ml/min flow rate.

## EFFECT OF CHEVRON CHASER CS1010 ON THE RHEOLOGICAL PROPERTIES OF WATER-IN-HEAVY OIL EMULSIONS:

The results of the rheological measurements done on stored samples are shown in Figures 2 through 5. For the most part, the rheological behaviour of these storage samples was as expected. The plots of shear stress vs. shear rate show that, generally, the behaviour of the emulsions at temperatures less than 150 C was either pseudoplastic or Newtonian usually with little or no hysteresis (within experimental error). The behaviour at 150 C appeared to be mildly dilatant. It should be said that because of the limitations of the rheometer the shear rate range was different at each temperature. Therefore, it is not clear whether this change in the behaviour is a temperature effect or a shear rate effect. Most of the surfactant-free emulsion curves show an increase in the slope with storage time, indicating an increase in apparent viscosity. The emulsions containing surfactant show either unchanged behaviour (within

experimental error), or even a decrease in slope with storage time, indicating a decrease in apparent viscosity. There are occasional reversals of this trend of increasing viscosity with time, however, it must be mentioned that the temperatures at which these curves were measured may have varied as much as ±1 C from the set temperature, and that these variations could account for the slight shifts shown in some of the graphs.

As for the influence of CS1010, the rheological measurements showed very little change for the Wolf Lake emulsion at all temperatures and storage times. However, the Pan Canadian emulsion, having greater water content, showed significant overall viscosity reduction at 100 C and 150 C for all storage times. The behaviour of PCC100 in Fig. 3c shows a large amount of hysteresis which diminished in magnitude with time. It also shows a shear thinning behaviour mentioned earlier in the introduction (8,10).

The droplet size distributions were determined from the bulk sample prior to any heating and the results appear as Figs. 6 through 9. It can be seen that the drop size distribution changed during storage. Keeping in mind that these are very crude measurements of the drop size distribution, the general trend with time is the disappearance of very small drops and narrowing of the drop size distribution. Comparing Figures 6 and 7, it is apparent that the presence of CS1010 has an effect on drop size distribution and that it promotes drop coalescence and phase separation. Although there are slight variations between the various emulsions, which may be due to artifacts of the measurement technique, they all follow approximately the same behaviour to give more sharply defined emulsions centred between one and three microns. The exception is PCR which ends up with a large population of droplets between one and two microns.

## FLOW BEHAVIOUR OF WATER-IN-HEAVY OIL EMULSIONS IN POROUS MEDIA:

Figures 10 through 17 present the pressure drop and water saturation data collected during the flow experiments. Referring to Fig. 10 , the data is plotted to show changes in pressure drop and water saturation with pore volumes of emulsion injected into the core. The figure also shows the changes in temperature during the course of the experiment. Comparing the steady-state pressure drops in absence

of any added surfactant (Fig. 10A) with that in presence of CS1010 (Fig. 10 B), it is apparent that the surfactant lowered the pressure drop by nearly 50%. It should be mentioned that the waviness in the pressure drop data was caused by changes in the room temperature. The free water saturation values, as measured by the micro-wave attenuation technique are also shown in the same figure. In the surfactant free system, the emulsion was injected into a water filled sand pack. This is the reason why the water saturation starts at 100% and then declines sharply as the displacing emulsion front reaches the measurement point. The free water saturation in this test reached a stable value of about 26% which remained unaffected by the flow rate and small fluctuations in the temperature. As shown in Fig. 10B, the free water saturation is lower in the presence of CS1010. In this case the surfactant containing emulsion was displacing a surfactant free emulsion. Therefore, the water saturation starts at what ever value existed for the previous emulsion. If it is assumed that the relative permeability characteristics are not altered by the presence of the surfactant, this lower saturation of free water would imply lower flowing fraction of the separated water phase. However, the analysis of the produced emulsions showed that the volume fraction of emulsified water was lower in presence of the surfactant. This suggests that in the surfactant containing system a larger fraction of water was flowing as a separated phase. There are two possible explanations for the observed behaviour. The presence of surfactant may have changed the relative permeability of the system in a way that allows more water to flow at a lower saturation, i.e. the irreducible water saturation was reduced by the surfactant. Secondly, it is conceivable that the surfactant containing system actually had more emulsified water in the porous medium but in the process of collecting a sufficient volume of the produced fluids, a large portion of this emulsified water dropped out. Unfortunately, it is not possible to resolve this issue without additional experimental work.

The next three figures (Fig. 11 to 13) show similar data at elevated temperatures. At 50°C the behaviour was same as at the room temperature. The presence of surfactant lowered the pressure drop and the free water saturation. The reduction in pressure drop was most pronounced at the highest flow rate. At 100°C the effect of surfactant on pressure drop and free water saturation almost disappeared. The free water saturation was of similar magnitude with and without the surfactant. However, the surfactant

containing system showed variations in the free water saturation with flow rate while the surfactant free system had same water saturation at all flow rates. Also at the lowest flow rate the free water saturation in the surfactant containing system appeared to be unstable, suggesting that the water was in a borderline state between being a free phase and being emulsified.

At 150 °C also the effect of CS1010 on pressure drop was very small. Free water saturation could not be measured at this temperature due to the limitations of the microwave transparent flow cell.

In summary for the Pan Canadian system the addition of Chevron Chase CS1010 lowered the pressure drop. However, this flow enhancement effect diminished with increasing temperature. The free water saturation also decreased in the presence of this surfactant and the surfactant made the free water saturation flow rate sensitive.

The results obtained with the Wolf Lake emulsion showed similar trends. At room temperature the surfactant reduced the pressure drop by approximately 40% and the free water saturation was lower in the surfactant containing system. The effect of the surfactant was of similar magnitude at 50°C. The differences in the results obtained with and without the surfactant were much smaller at higher temperatures, however, the surfactant was still showing some positive effects at 150°C.

Referring to Figs. 18 through 24, the effect of flow through porous media on emulsion droplet size distribution is now examined. The droplet size distributions for the various emulsions on entry into the core are represented by figs. 6a, 7a, 8a, and 9a since samples of these emulsions were frozen in individual jars for this part of the work. Within the experimental error, and considering the method by which the size distributions were generated, only some general observations can be made. One such observation is that varying flow rates do not seem to have a large effect on the produced size distribution. It also appears that, to some extent, the produced size distributions of the emulsions containing CS1010 are similar to their entry condition size distributions.

During most of the flow experiments, it was found that a portion of the emulsified water was produced from the core as a bulk phase. The emulsions used in flow tests at low temperatures retained most of their emulsified water, while those used at higher temperatures lost more of their emulsified water.

These results are plotted in figs. 25a-d. The plotted values are for the emulsion phase after separation of the bulk phase water. Interestingly, a general trend shown by the plots indicate that for all the flow conditions except Wolf Lake at 23 C, there was less emulsified water in the produced emulsions containing CS1010 than there was in the produced emulsions that did not contain the surfactant. The results also show that, as a function of temperature, generally the emulsified water content decreases with increasing temperature. Examination of the results as a function of flow rate within a constant temperature, the results show a more emulsion specific trend. For the Wolf Lake emulsion, the retained emulsified water content appears to decrease with increasing flow rate (within experimental error). For the Pan Canadian emulsion, the retained emulsified water content appears to increase slightly with increasing flow rate, with the exception of the PCC150 results.

As mentioned previously, after the emulsion was separated from bulk phase water, the rheology of the sample was determined. The results were plotted and appear as Figs. 26 and 27. The power law fitted coefficients and correlation coefficients appear in table 1. As explained earlier, the initial values for the emulsion rheologies are from day 0 of the storage results.

# DISCUSSION

The accumulated results of this work beg the question of what role the CS1010 surfactant plays at the microscopic level. From the results, one plausible explanation may be that the surfactant acts as a demulsifier. Referring to the results of the produced emulsion water content, Figs. 25a-d, it can be seen that virtually all emulsions containing CS1010 had lower emulsified water contents than their surfactant-free counterparts. Furthermore, it was observed that the surfactant containing emulsions showed water separation when stored at a slightly elevated temperature.

On the other hand, the flow through porous media experiments showed smaller free water saturation in surfactant containing systems. This appears to suggest, although not conclusively, that in the surfactant containing system, more water was flowing as an emulsion. The surfactant, therefore, may have helped in maintaining the emulsion within the porous medium. Since the pressure drop in the surfactant containing system was much lower than the surfactant free system at identical flow rates, it is certain that the flowing emulsion had very different characteristics in the presence of the surfactant. These differences in the flowing emulsion characteristics could lie in the volume fraction of emulsified water, the drop size distribution or the viscoelastic properties of the adsorbed interfacial layer of the emulsifiers. It is conceivable that a combination of changes in the drop size distribution and viscoelastic properties of the interface can lead to reduced pressure drop at higher volume fraction of emulsified water.

It is interesting to note that the surfactant had only a minor effect on the bulk rheological properties. This suggests that the mechanism responsible for the reduction in pressure drop in flow through porous media was not operative in the shear stress versus shear rate measurements in a rotational viscometer. It should be mentioned that the size of the gap between the concentric cylinders of the rotational viscometer is two to three orders of magnitude larger than the mean diameter of the emulsion droplets while the size of pore constrictions is comparable to the drop sizes. Therefore the drops must deform considerably during passage through pore throats. Such deformations may not be required in the concentric cylinder geometry

of the rheometer. Therefore the visco-elastic properties of the adsorbed monolayers could play a more important role in the flow through porous media. Thus another plausible explanation of the observed behaviour is that the surfactant reduces the interfacial viscosity at the oil/water interface, thereby facilitating the passage of individual droplets through pore throats. This reduction in the interfacial viscosity mode of action is also consistent with the observed effect of temperature. It is likely that the interfacial viscosity is reduced to such an extent by increased temperature that even in the surfactant free system the droplet can pass through pore throats without much expenditure of energy. Thus the reduction in interfacial viscosity by the surfactant becomes an insignificant factor.

Yet another possible mechanism involves equilibrium and dynamic interfacial tensions. It is more than likely that the added surfactant reduces interfacial tension significantly. More importantly it may have a significant effect on the dynamic interfacial tension. Since in flowing through the tortuous flow paths of porous media droplet surfaces expand and contract rapidly, the dynamic interfacial tension can be an important factor.

Of course, it would be desirable to measure the effect of surfactant on the visco-elastic properties and dynamic interfacial tension of the oil-water interface directly. Unfortunately, we did not have access to the instruments needed for such measurements. Also due to the difficulties in obtaining reproducible samples, the complex crude oil emulsions are not the best material for studying the basic mechanisms of emulsion flow in porous media. We believe that at this stage investigations of basic mechanisms with relatively pure systems would be preferable.

In summary, we found that the presence of Chevron Chaser CS1010 did have a beneficial effect on flow properties of the tested water-in- heavy oil emulsions. The mechanism responsible for this effect of the additive could not be determined conclusively. The alteration of visco-elastic properties of the oil-water interface may be an important factor. To determine the mechanism involved in the observed surfactant induced flow enhancement it would be necessary to conduct a systematic study of various possible mechanisms in simpler systems.

# CONCLUSIONS AND RECOMMENDATIONS

1. An emulsion flow apparatus capable of bulk phase point water saturation detection was made operational.
2. Storage of surfactant-free emulsion at room temperature caused a gradual increase in apparent viscosity with time.
3. Storage of emulsion containing surfactant at room temperature caused either no change or a slight decrease in the apparent viscosity with time.
4. The addition of Chevron CS1010 surfactant to the two emulsions tested in this study gave lower pressure drops than equivalent emulsion systems containing no added surfactant.
5. The mechanism responsible for the pressure drop reduction could not be determined conclusively.
6. The systems containing Chevron Chaser CS1010 had lower free water saturations compared to the surfactant free systems.
7. All emulsions emerging from the core contained less water than that in the injected emulsions, and also appeared to be less viscous than the initial material before entering the core.

The results obtained in this experimental study have shown that chemical additives can indeed provide significant flow enhancement in systems involving flow of water-in-oil emulsions through porous media. The study has also raised several interesting questions regarding the mechanism responsible for such flow enhancement. It is not clear whether or not a direct correlation exists between the effect of the additive on bulk rheological properties and flow behaviour in porous media. This aspect should be investigated in depth. It appears that the flow conditions existing within the porous medium (velocity, pressure gradient and wettability) play a role in determining the drop size distribution and volume fraction of the dispersed phase in the flowing emulsion. However, the kinetics of the change in emulsion characteristics resulting from flow in porous media and the role of the previous history of the emulsion is

not clear. This issue needs to be examined systematically before a mathematical model to describe emulsion flow in porous media can be developed. Finally the relationship between visco-elastic properties of the oil/water interface and the flow behaviour of water-in-oil emulsions must be investigated to get an insight into the basic mechanisms involved in flow of water-in-oil emulsions through porous media.

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**Table 1: Values of the Power Law Constants* Fitted to the Experimental Data.**

| SAMPLE | n | B | correlation coeff. |
|---|---|---|---|
| PCC23, INITIAL | 0.974 | 52.119 | 0.999975 |
| PCC50, INITIAL | 0.923 | 4.529 | 0.999603 |
| PCC100, INITIAL | 0.752 | 0.684 | 0.987962 |
| PCC150, INITIAL | 1.086 | 0.022 | 0.999445 |
| PCR23, INITIAL | 0.924 | 47.098 | 0.998184 |
| PCR50, INITIAL | 0.939 | 4.150 | 0.999846 |
| PCR100, INITIAL | 0.968 | 0.241 | 0.999817 |
| PCR150, INITIAL | 1.152 | 0.018 | 0.998590 |
| WLC23, INITIAL | 1.160 | 35.075 | 0.998656 |
| WLC50, INITIAL | 0.934 | 3.715 | 0.997902 |
| WLC100, INITIAL | 0.977 | 0.195 | 0.999647 |
| WLC150, INITIAL | 1.148 | 0.014 | 0.999346 |
| WLR23, INITIAL | 0.985 | 51.286 | 0.999543 |
| WLR50, INITIAL | 1.016 | 3.350 | 0.999701 |
| WLR100, INITIAL | 0.975 | 0.174 | 0.999700 |
| WLR150, INITIAL | 1.175 | 0.011 | 0.999611 |
| PCR23-.01 | 0.942 | 30.479 | 0.999650 |
| PCR23-.02 | 0.982 | 20.559 | 0.999025 |
| PCC23-.01 | 0.930 | 17.179 | 0.998808 |
| PCC23-.02 | 0.917 | 18.750 | 0.999473 |
| WLR23-.005 | 1.016 | 52.240 | 0.999641 |
| WLC23-.005 | 0.840 | 43.954 | 0.999188 |
| PCR50-.05 | 1.038 | 1.045 | 0.999780 |
| PCR50-.1 | 0.989 | 1.496 | 0.999604 |
| PCR50-.2 | 0.979 | 1.722 | 0.999075 |
| PCC50-.05 | 0.944 | 1.449 | 0.999937 |
| PCC50-.1 | 0.969 | 1.400 | 0.999845 |
| PCC50-.2 | 0.929 | 1.503 | 0.999859 |
| WLR50-.05 | 0.974 | 2.704 | 0.999609 |
| WLR50-.1 | 0.935 | 3.428 | 0.999849 |
| WLR50-.2 | 0.951 | 3.236 | 0.999504 |
| WLC50-.05 | 0.981 | 2.084 | 0.999897 |
| WLC50-.1 | 0.812 | 4.571 | 0.998834 |
| WLC50-.2 | 0.880 | 3.133 | 0.998209 |
| PCR100-2 | 0.970 | 0.108 | 0.999428 |
| PCR100-1 | 0.986 | 0.098 | 0.998459 |
| PCR100-.5 | 0.934 | 0.146 | 0.999798 |
| PCC100-2 | 0.895 | 0.172 | 0.999452 |

| | | | |
|---|---|---|---|
| PCC100-1 | 0.942 | 0.127 | 0.999913 |
| PCC100-.5 | 0.959 | 0.119 | 0.999422 |
| WLR100-2 | 0.973 | 0.164 | 0.999917 |
| WLR100-1 | 0.937 | 0.236 | 0.999701 |
| WLR100-.5 | 0.927 | 0.212 | 0.999728 |
| WLC100-2 | 0.945 | 0.173 | 0.999853 |
| WLC100-1 | 0.878 | 0.245 | 0.998842 |
| WLC100-.5 | 0.876 | 0.269 | 0.998748 |
| PCR150-9 | 1.331 | 0.003 | 0.999019 |
| PCR150-6 | 1.219 | 0.007 | 0.997194 |
| PCR150-3 | 1.303 | 0.004 | 0.998731 |
| WLR150-9 | 1.203 | 0.008 | 0.999422 |
| WLR150-6 | 1.154 | 0.012 | 0.995824 |
| WLR150-3 | 1.168 | 0.011 | 0.998158 |
| WLC150-9 | 1.244 | 0.005 | 0.995526 |
| WLC150-6 | 1.263 | 0.005 | 0.999265 |
| WLC150-3 | 1.119 | 0.011 | 0.999156 |
| PCC150-9 | 1.199 | 0.006 | 0.996345 |
| PCC150-6 | 1.219 | 0.006 | 0.997900 |
| PCC150-3 | 1.234 | 0.005 | 0.996770 |

* The listed constants are for the following equation:
(shear rate) = B (shear stress)$^{n}$

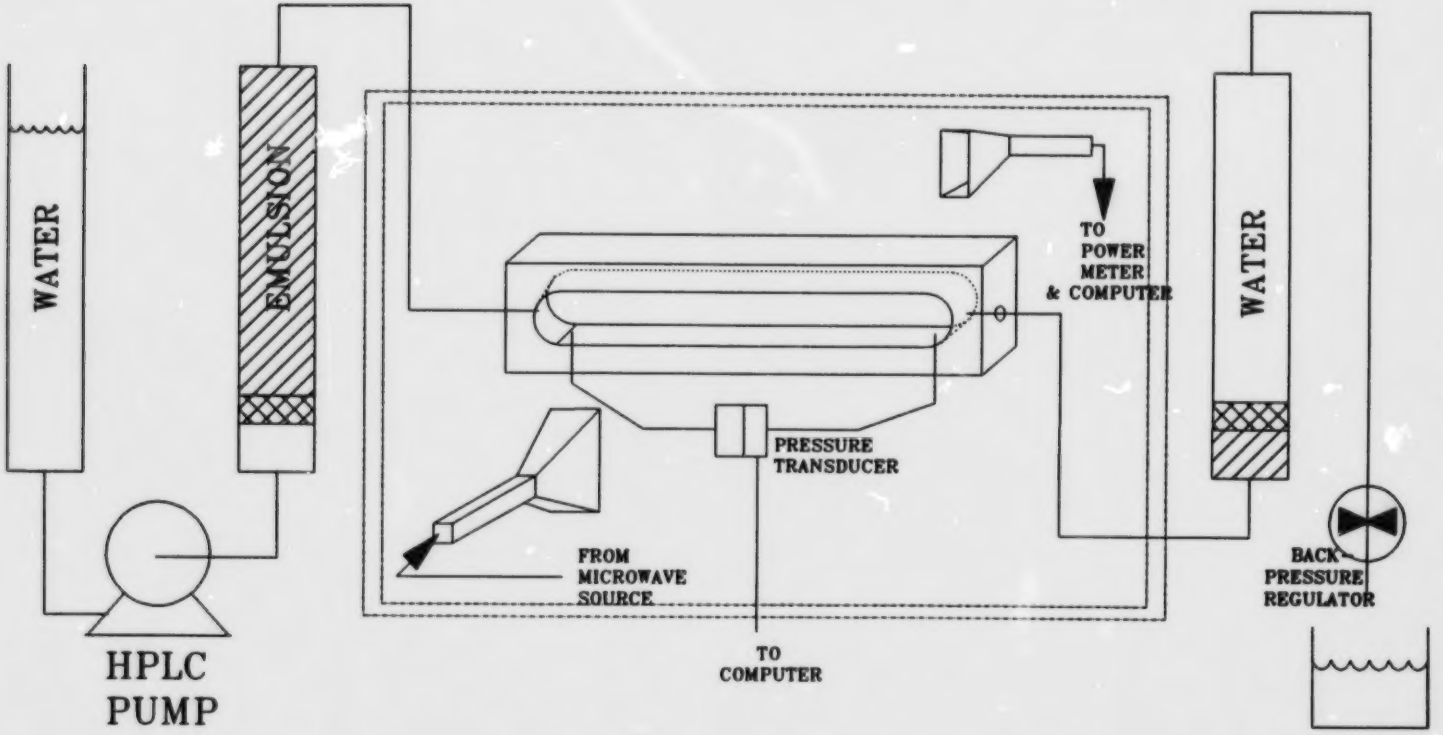


FIG 1A: EMULSION FLOW APPARATUS

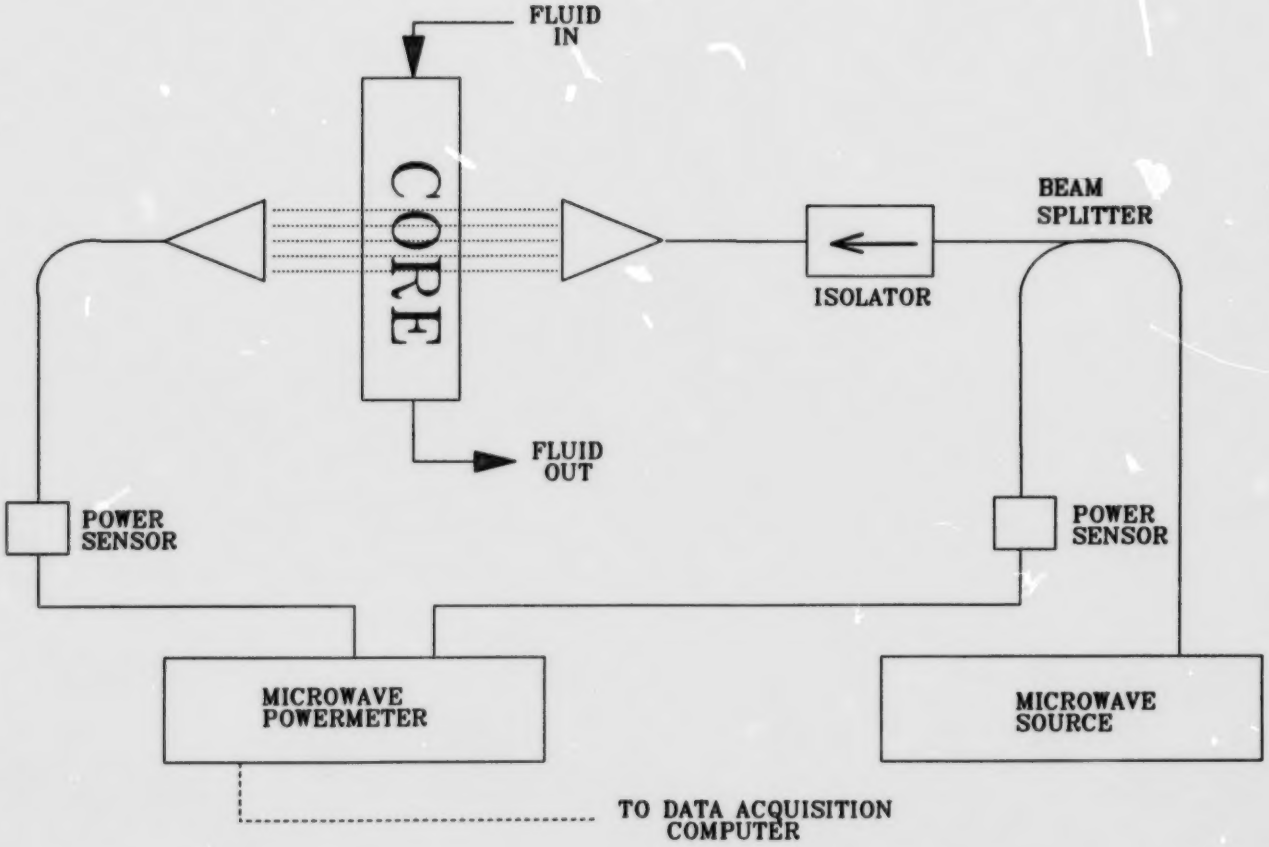


FIG. 1B: MICROWAVE SCHEMATIC OF EMULSION FLOW EXPERIMENT

FIG. 2A: SHEAR STRESS vs. SHEAR RATE
Stored Pan Canadian emulsion, data at 23 C

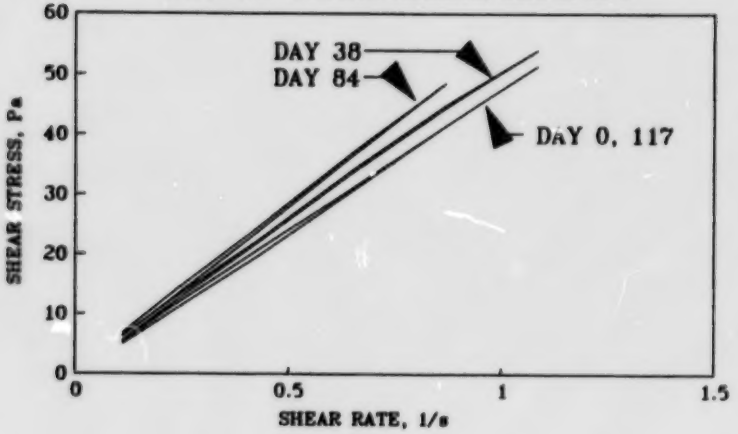


FIG. 2B: SHEAR STRESS vs. SHEAR RATE
Stored Pan Canadian emulsion, data at 50 C

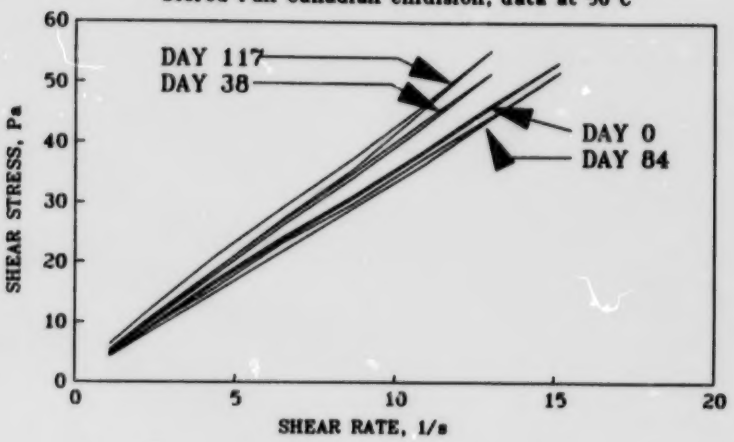


FIG. 2C: SHEAR STRESS vs. SHEAR RATE
Stored Pan Canadian emulsion, data at 100 C

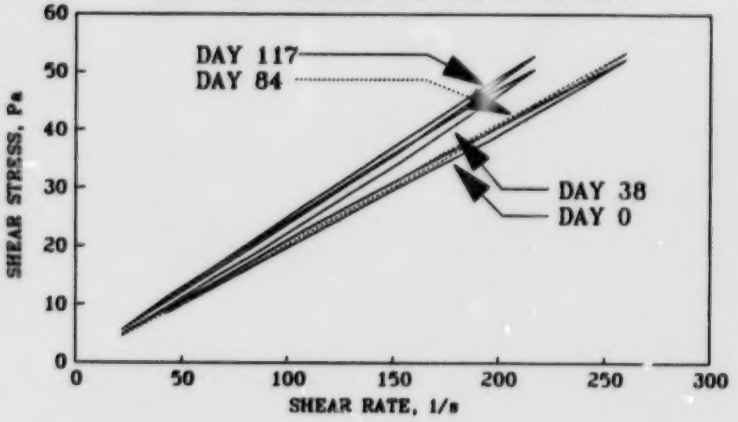


FIG. 2D: SHEAR STRESS vs. SHEAR RATE
Stored Pan Canadian emulsion, data at 150 C

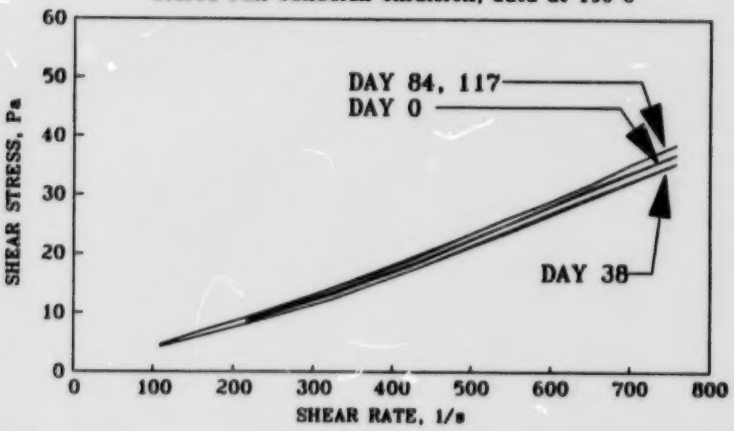


FIG. 2

FIG. 3A: SHEAR STRESS vs. SHEAR RATE

Stored Pan Canadian emulsion with CS1010, data at 23 C

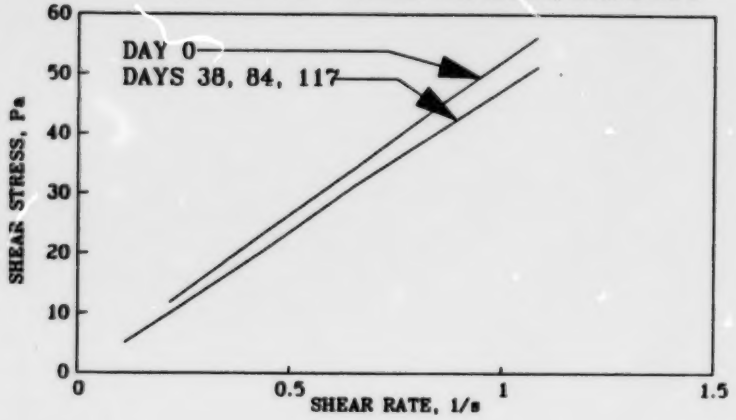


FIG. 3B: SHEAR STRESS vs. SHEAR RATE

Stored Pan Canadian emulsion with CS1010, data at 50 C

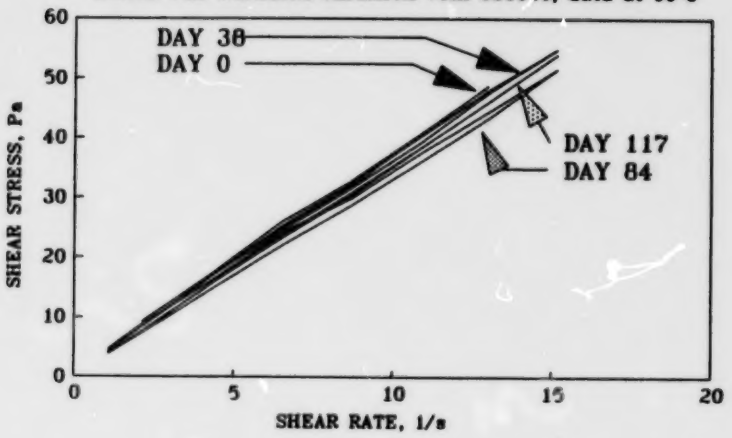


FIG. 3C: SHEAR STRESS vs. SHEAR RATE

Stored Pan Canadian emulsion with CS1010, data at 100 C

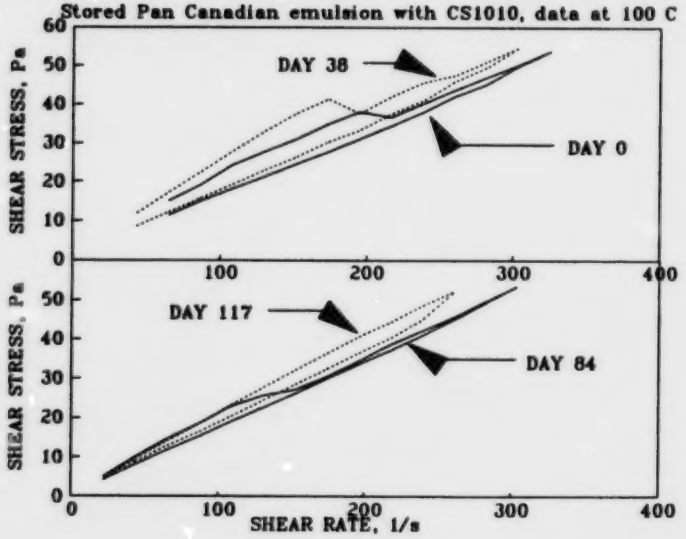


FIG. 3D: SHEAR STRESS vs. SHEAR RATE

Stored Pan Canadian emulsion with CS1010, data at 150 C

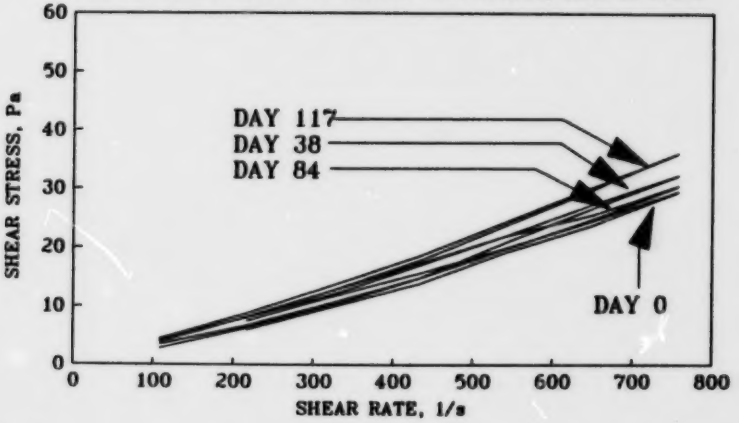


FIG. 3

FIG. 4A: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion, data at 23 C

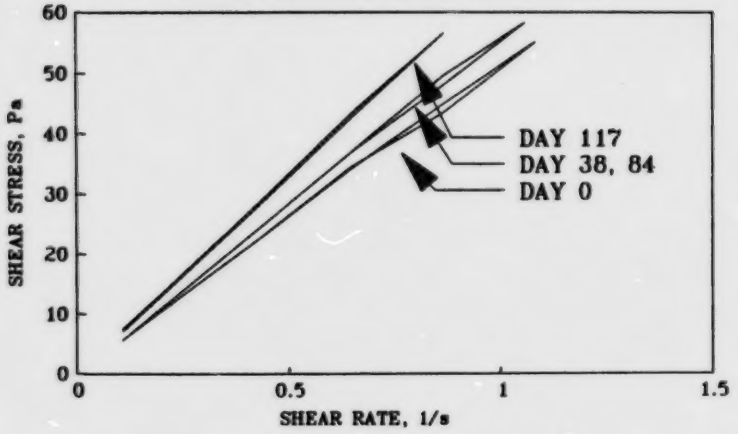


FIG. 4B: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion, data at 50 C

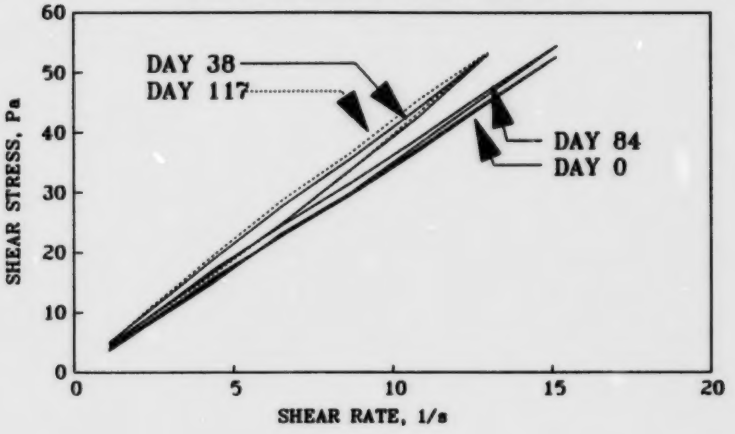


FIG. 4C: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion, data at 100 C

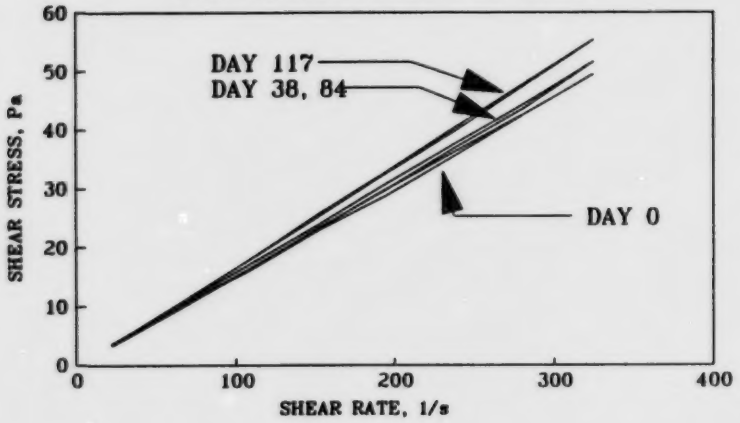


FIG. 4D: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion, data at 150 C

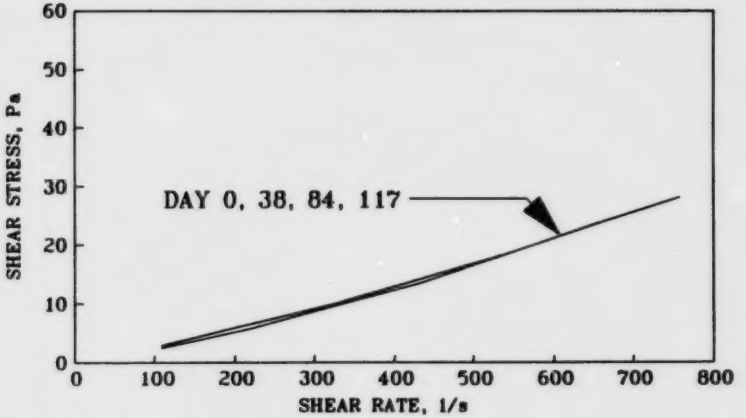


FIG. 4

FIG. 5A: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion with CS1010, data at 23 C

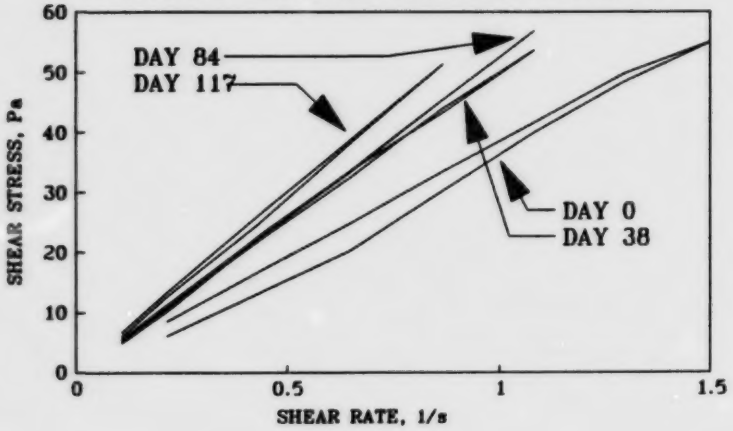


FIG. 5B: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion with CS1010, data at 50 C

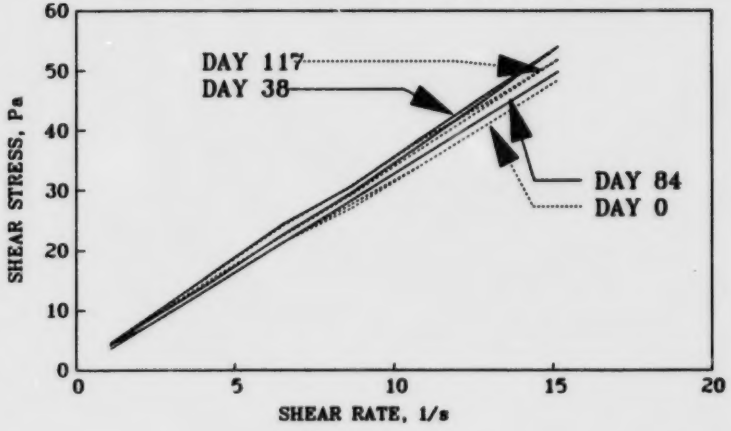


FIG. 5C: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion with CS1010, data at 100 C

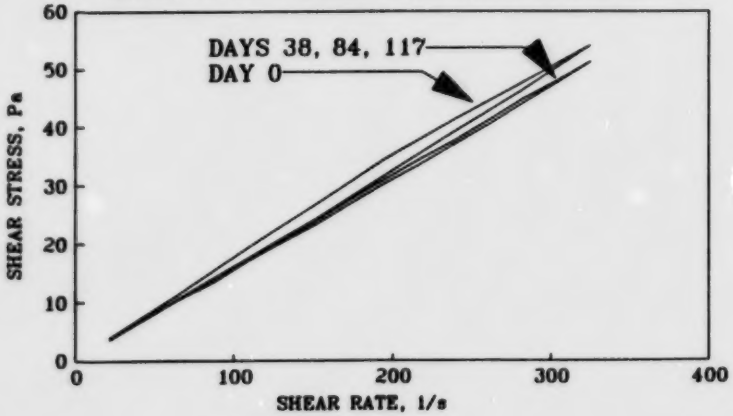


FIG. 5D: SHEAR STRESS vs. SHEAR RATE
Stored Wolf Lake emulsion with CS1010, data at 150 C

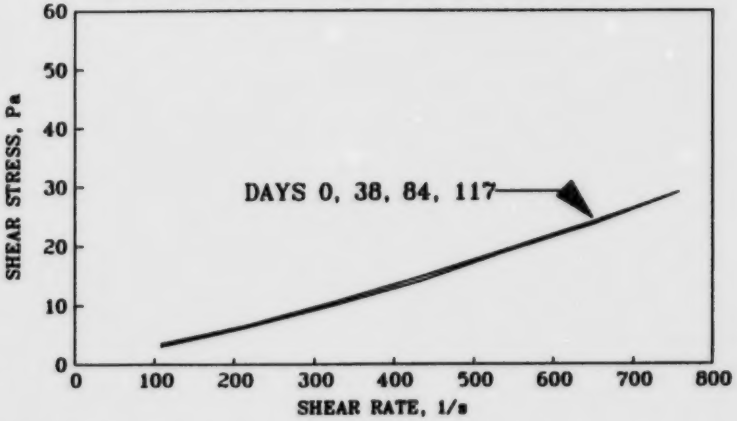


FIG. 5

FIG. 6A: Droplet Size Distribution
STORED PAN CANADIAN EMULSION, DAY 0

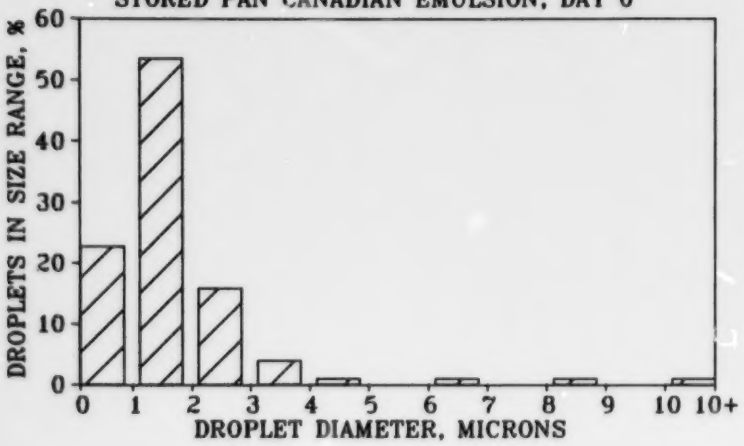


FIG. 6B: Droplet Size Distribution
STORED PAN CANADIAN EMULSION, DAY 38

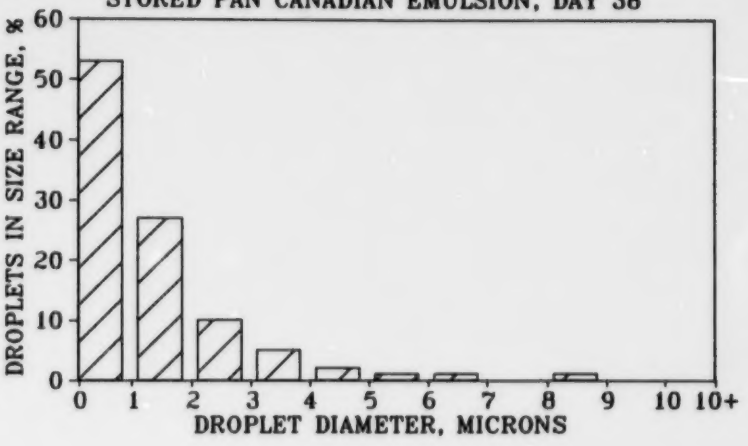


FIG. 6C: Droplet Size Distribution
STORED PAN CANADIAN EMULSION, DAY 84

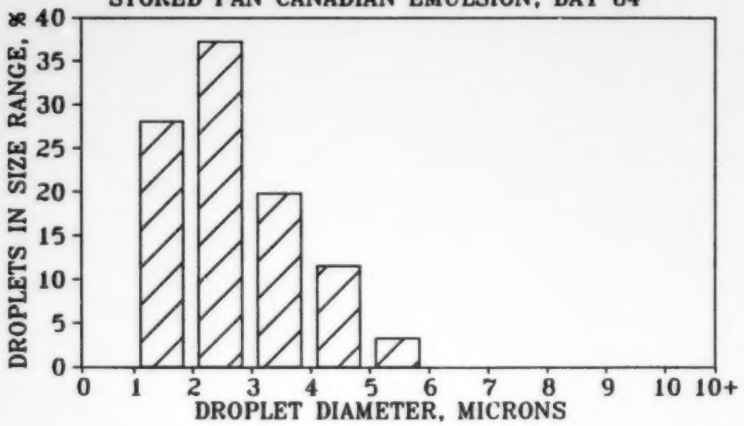


FIG. 6D: Droplet Size Distribution
STORED PAN CANADIAN EMULSION, DAY 117

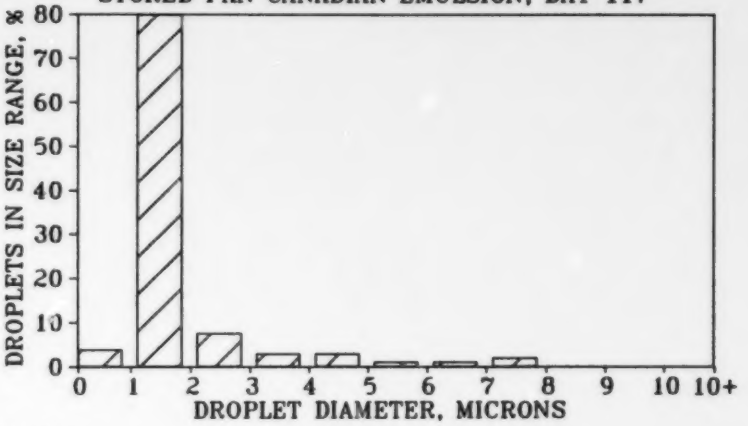


FIG. 6

FIG. 7A: Droplet Size Distribution

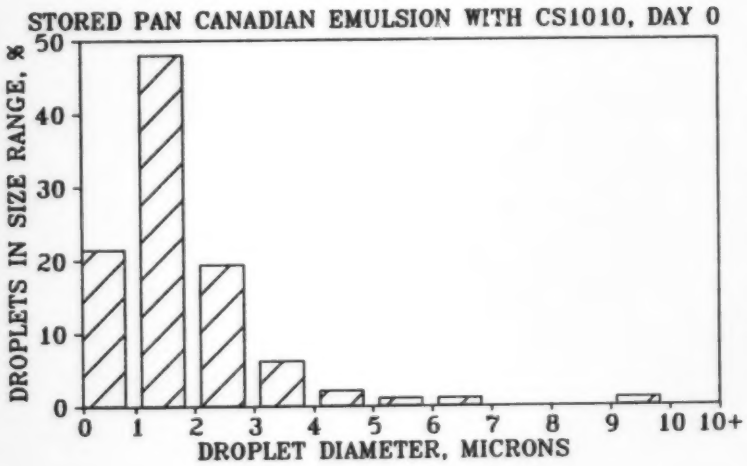


FIG. 7B: Droplet Size Distribution

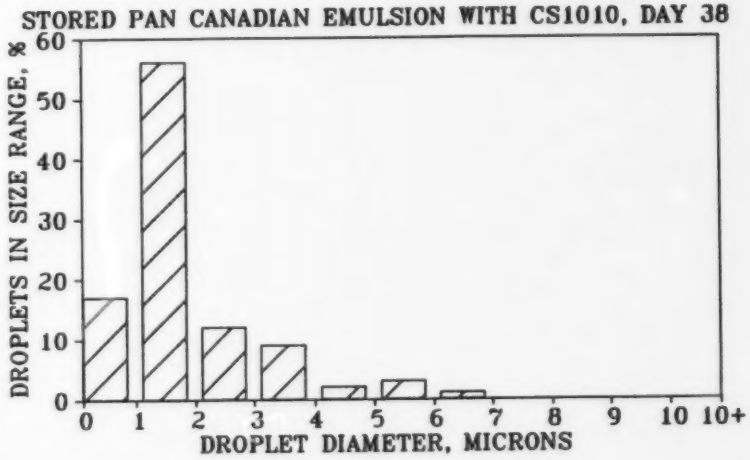


FIG. 7C: Droplet Size Distribution

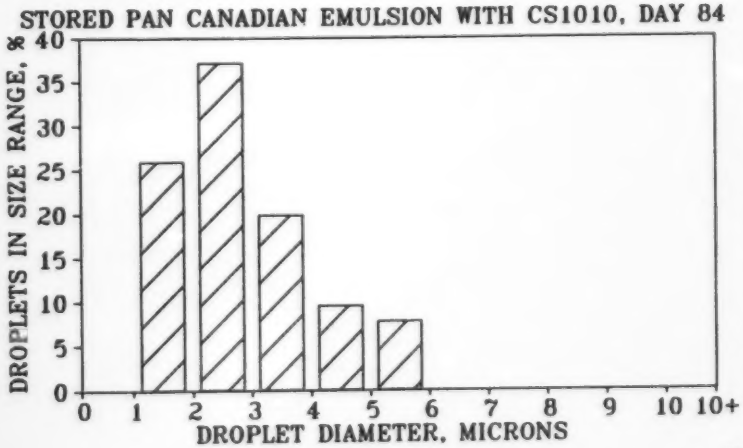


FIG. 7D: Droplet Size Distribution

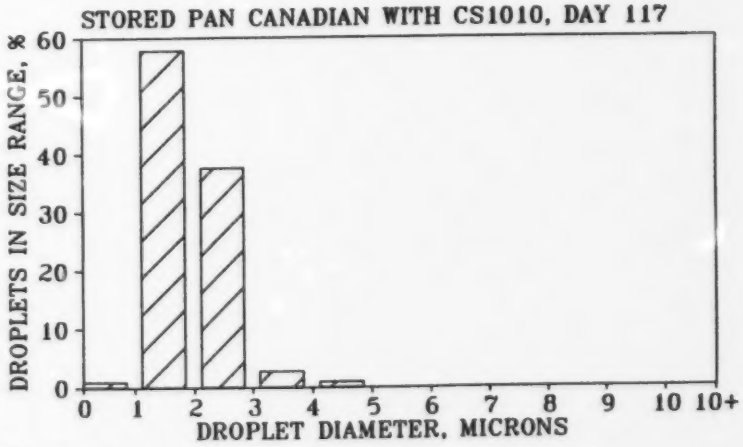


FIG. 7

FIG. 8A: Droplet Size Distribution

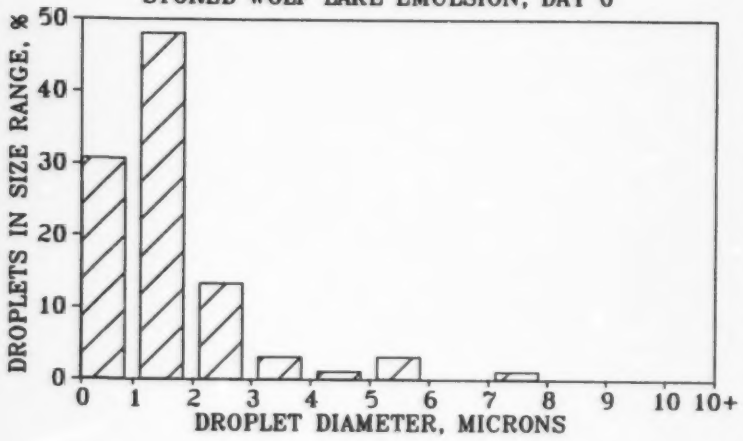


FIG. 8B: Droplet Size Distribution

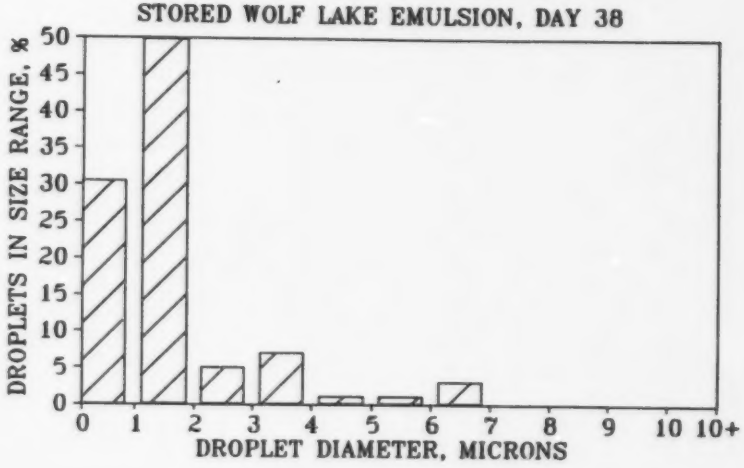


FIG. 8C: Droplet Size Distribution

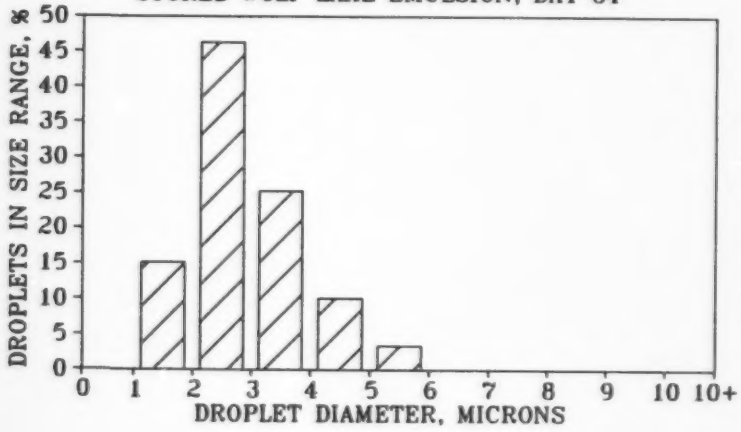


FIG. 8D: Droplet Size Distribution

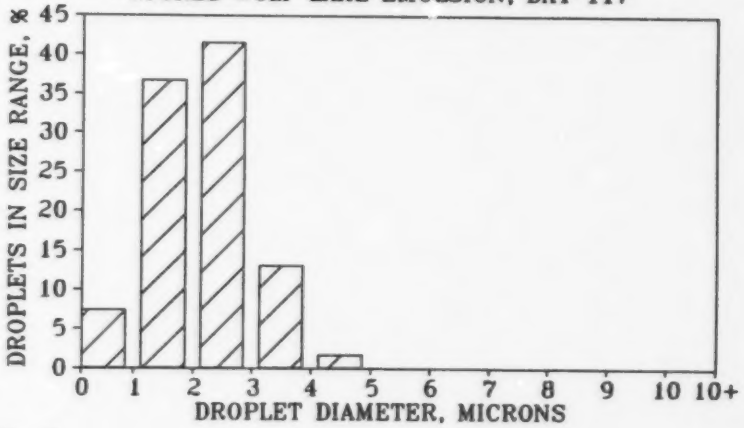


FIG. 8

FIG. 9A: Droplet Size Distribution

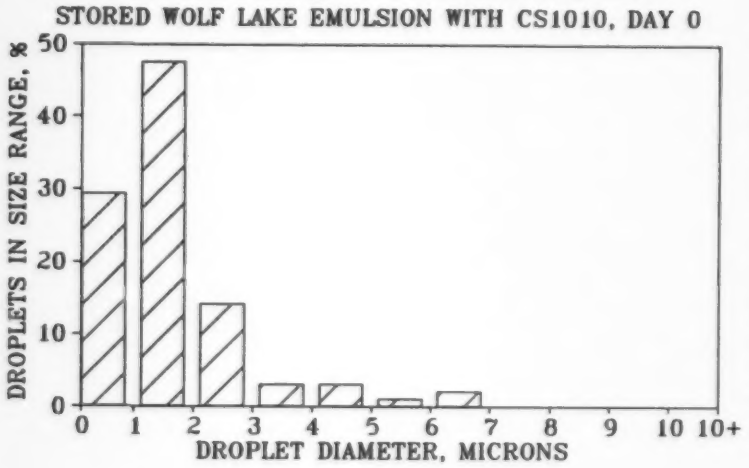


FIG. 9B: Droplet Size Distribution

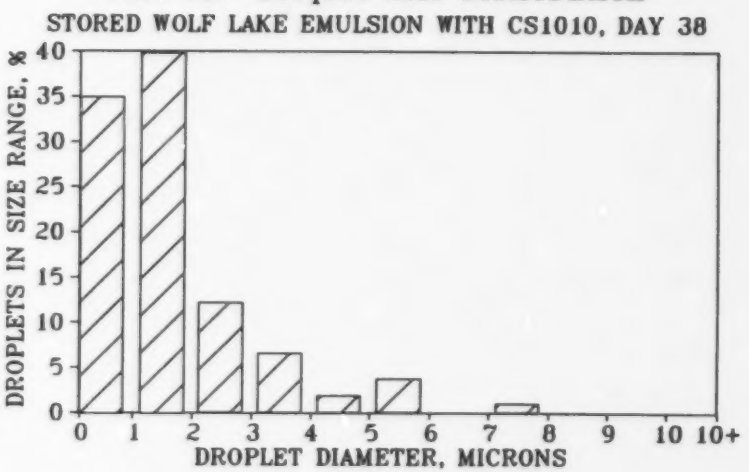


FIG. 9C: Droplet Size Distribution

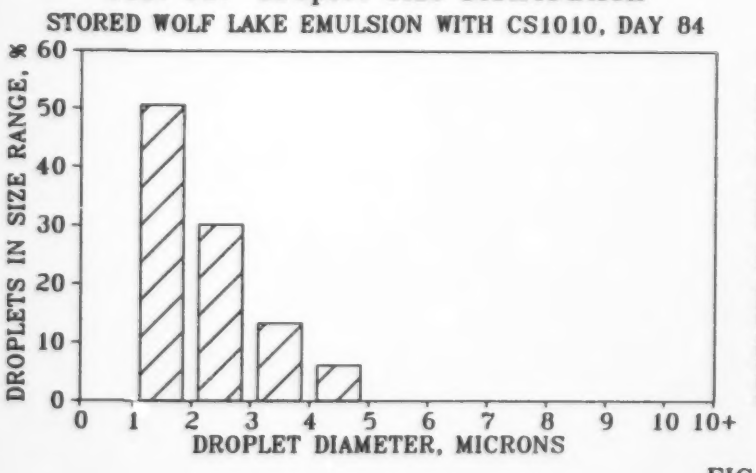


FIG. 9D: Droplet Size Distribution

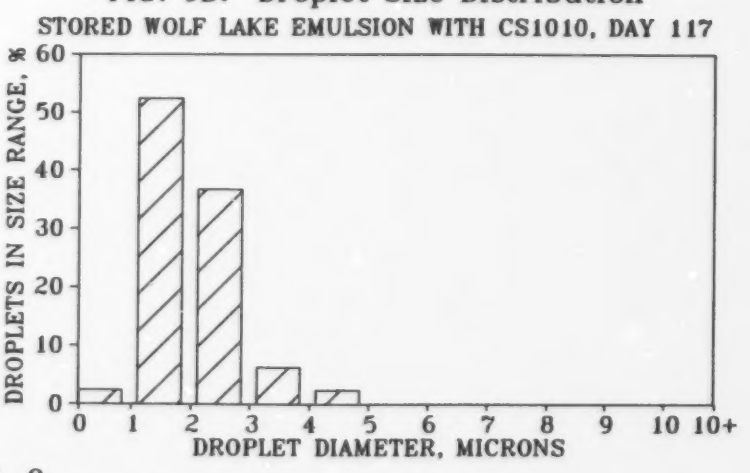


FIG. 9

FIG 10A: PAN CANADIAN EMULSION

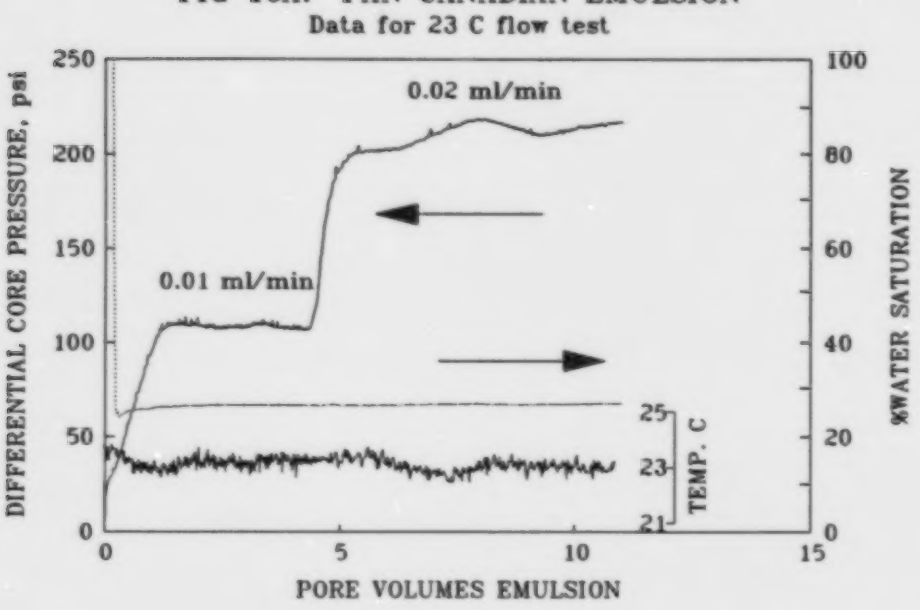


FIG. 10B: PAN CANADIAN EMULSION WITH CS1010

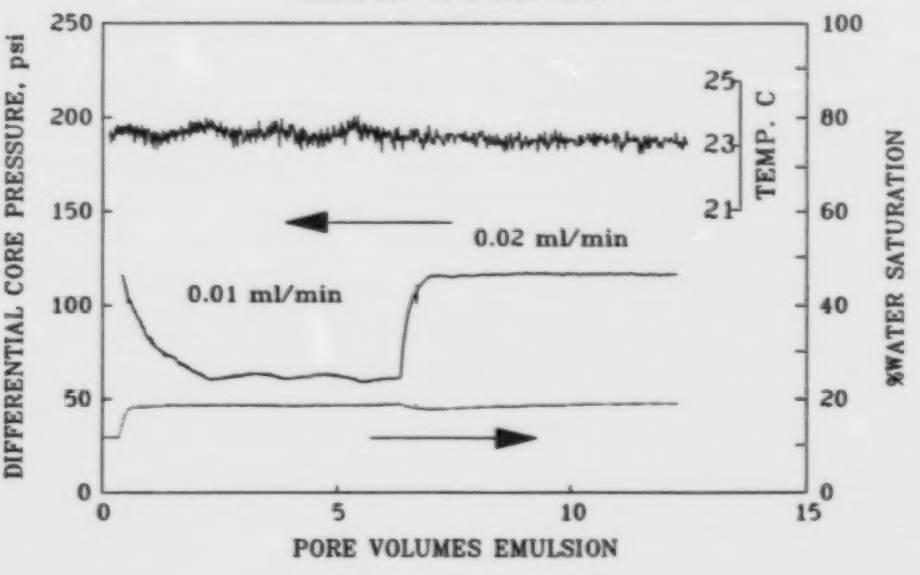


FIG. 10

FIG. 11A: PAN CANADIAN EMULSION

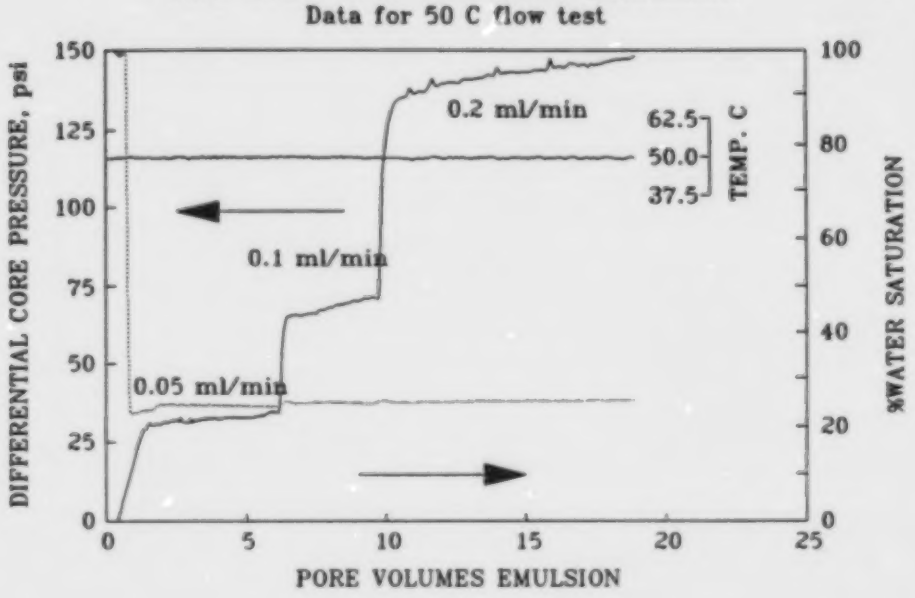


FIG. 11B: PAN CANADIAN EMULSION WITH CS1010

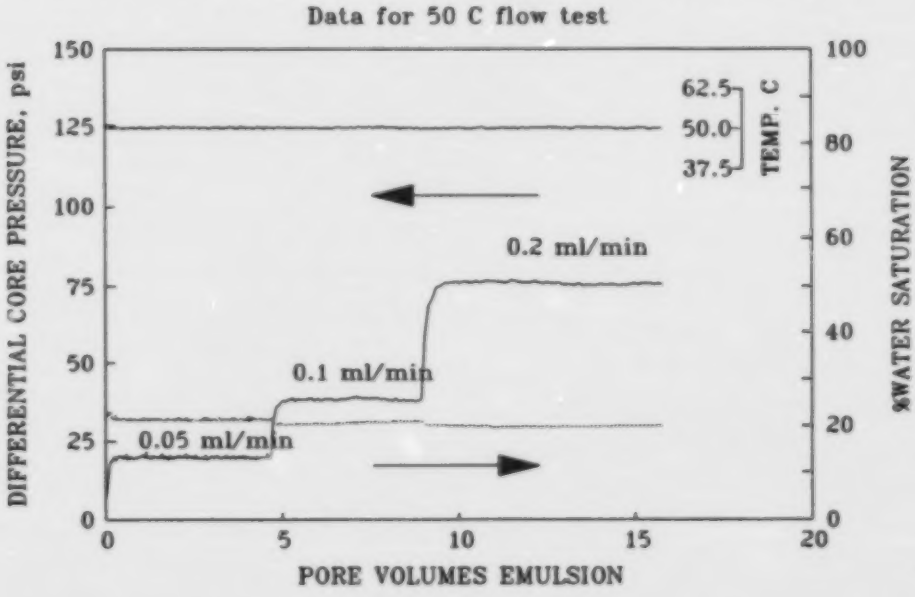


FIG. 11

FIG. 12A: PAN CANADIAN EMULSION

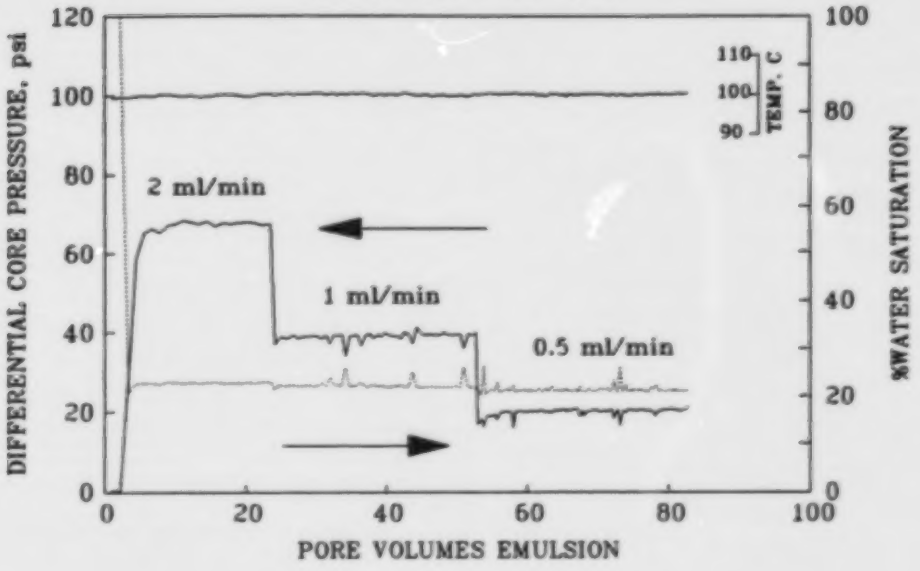


FIG. 12B: PAN CANADIAN EMULSION WITH CS1010

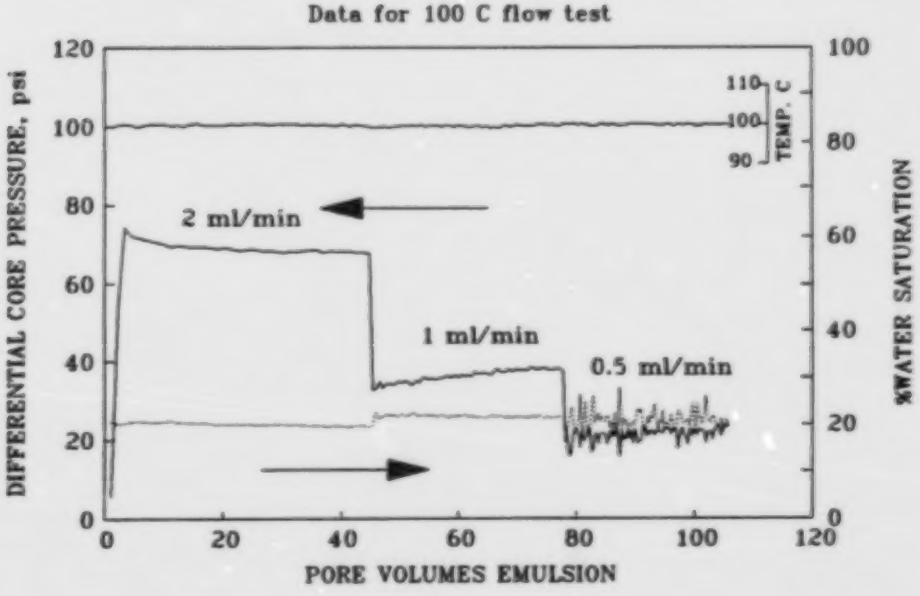


FIG. 12

FIG. 13A: PAN CANADIAN EMULSION
Data for 150 C flow test

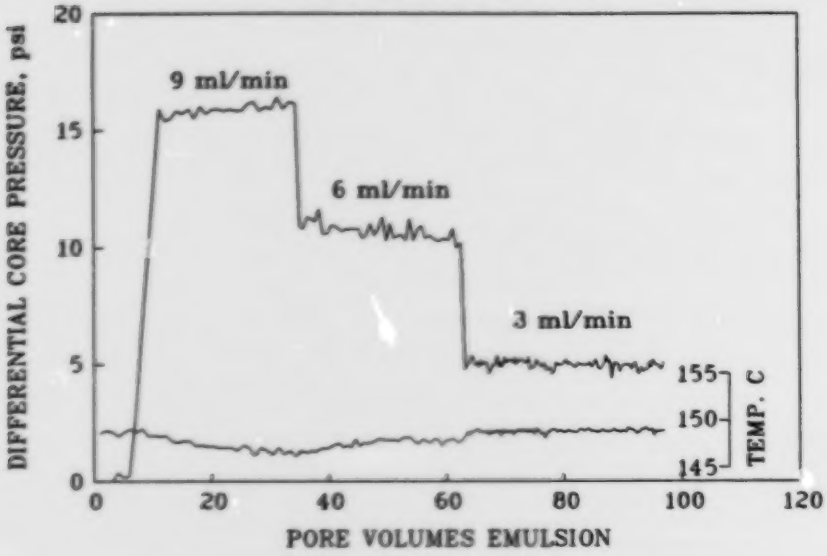


FIG. 13B: PAN CANADIAN EMULSION WITH CS1010
Data for 150 C flow test

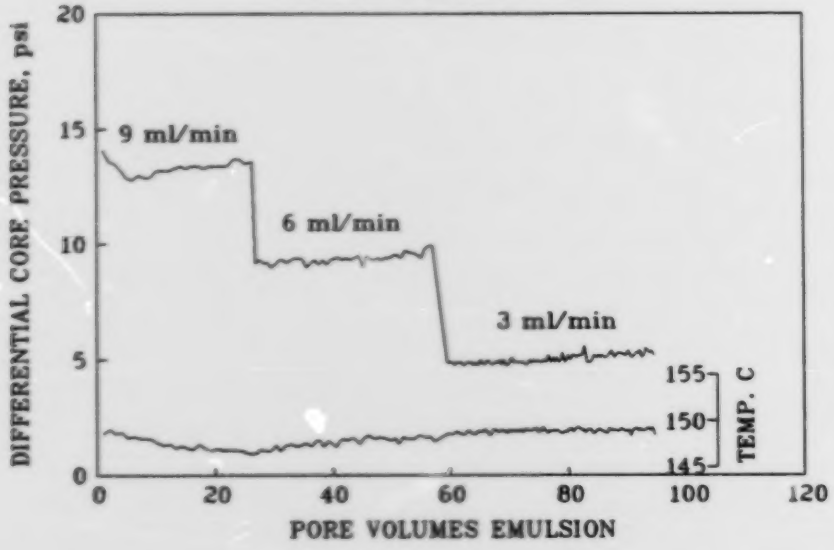


FIG. 13

FIG. 14A: WOLF LAKE EMULSION

Data for 23 C and 0.005 ml/min flow test

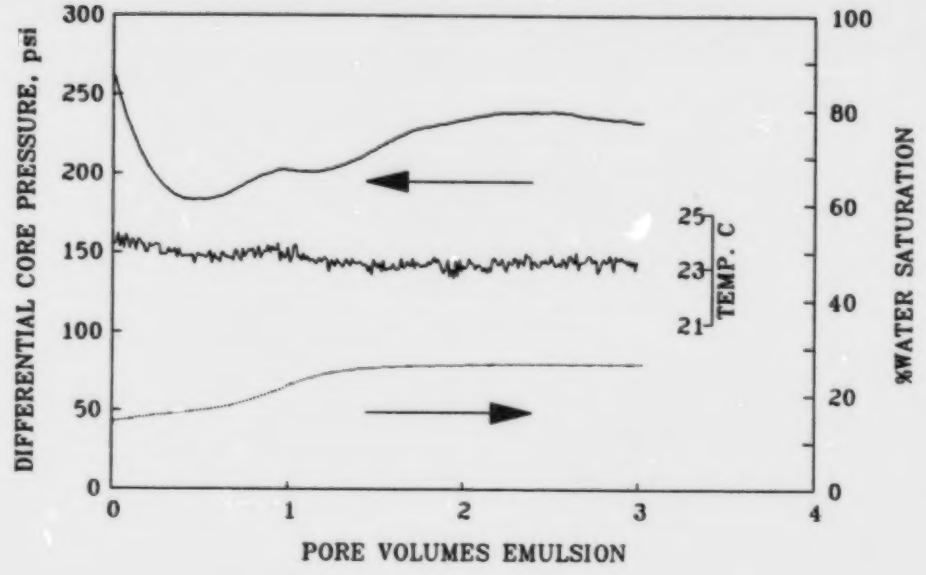


FIG. 14B: WOLF LAKE EMULSION WITH CS1010

Data for 23 C and 0.005 ml/min flow test

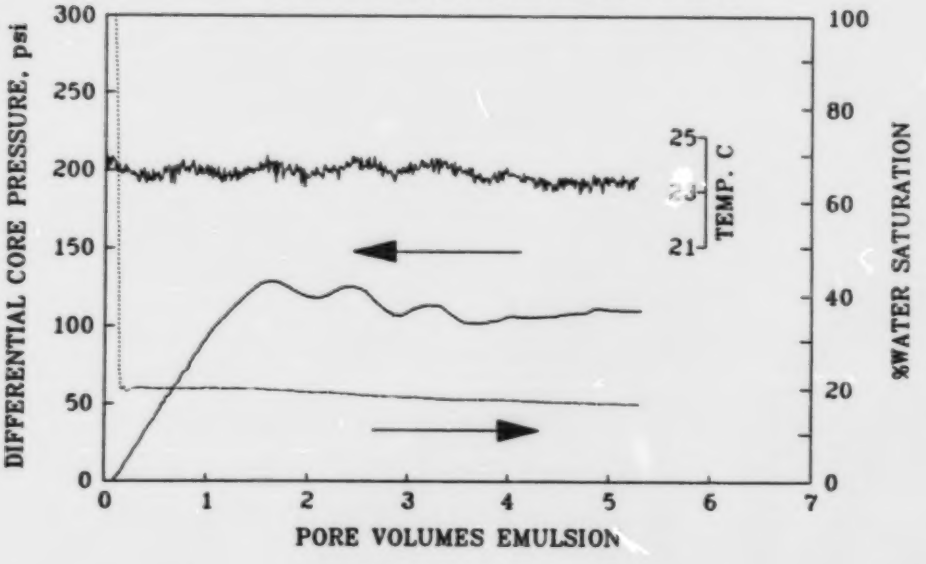


FIG. 14

FIG. 15A: WOLF LAKE EMULSION

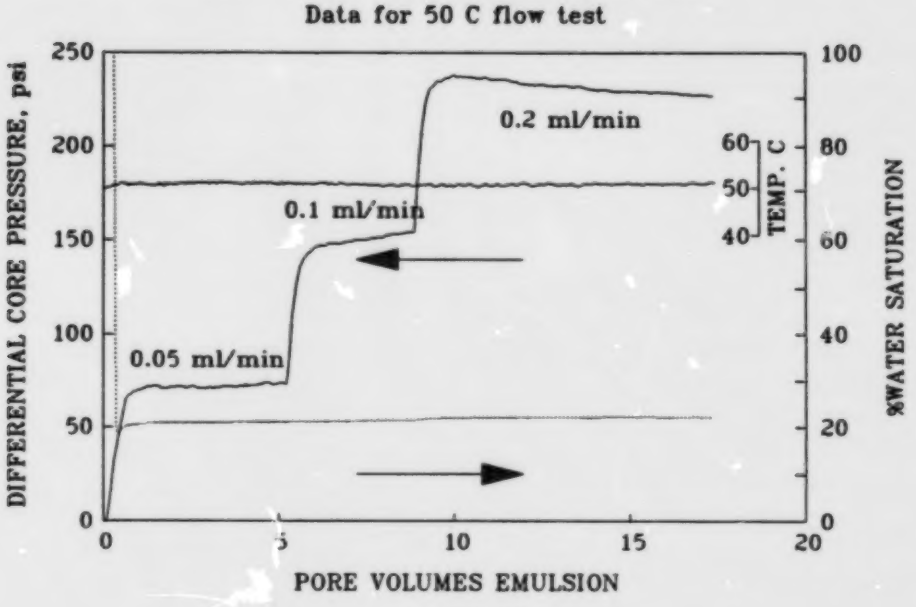


FIG. 15B: WOLF LAKE EMULSION WITH CS1010

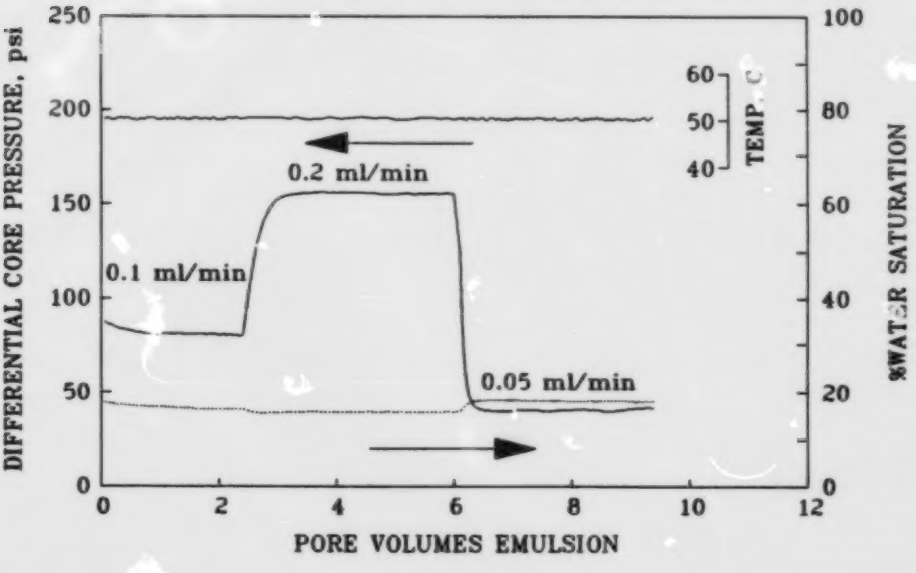


FIG. 15

FIG. 16A: WOLF LAKE EMULSION

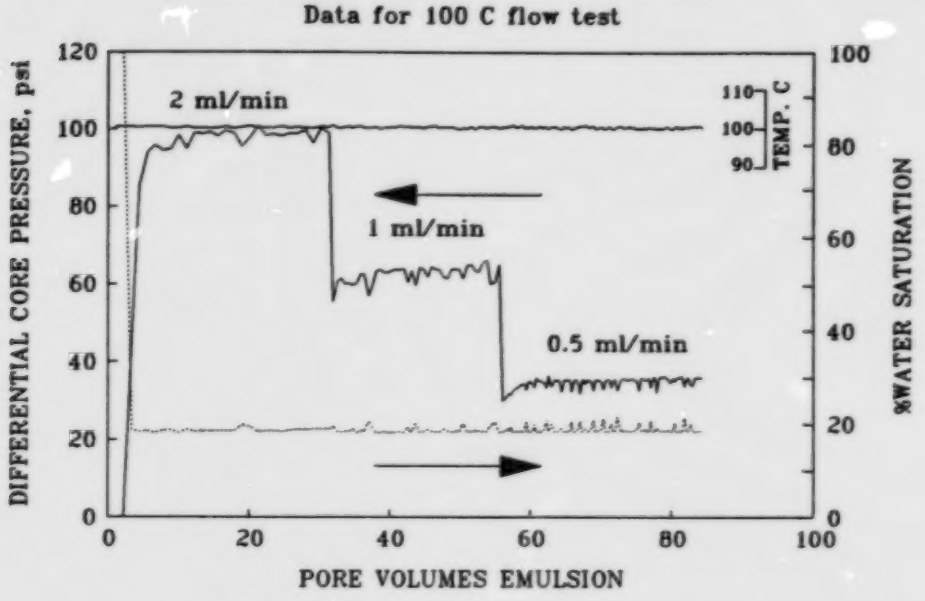


FIG. 16B: WOLF LAKE EMULSION WITH CS1010

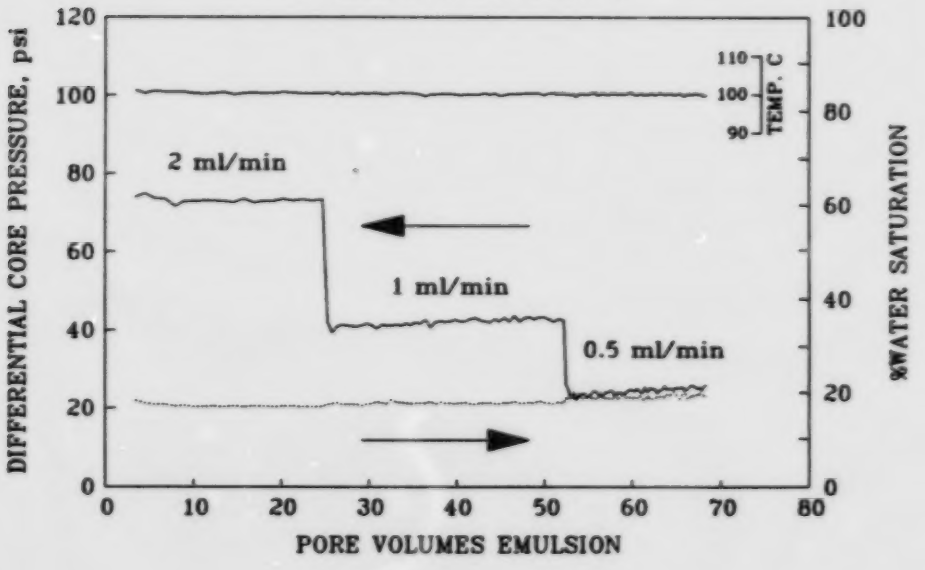


FIG. 16

FIG. 17A: WOLF LAKE EMULSION

Data for 150 C flow test

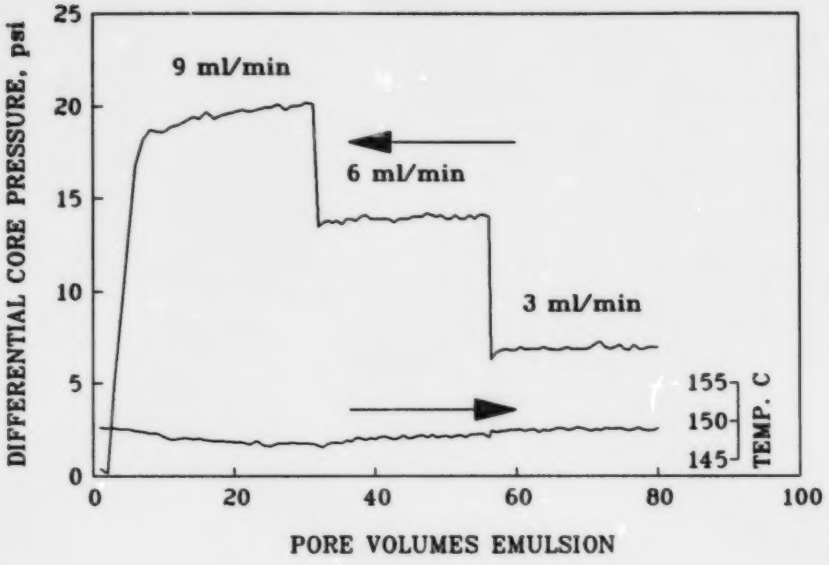


FIG. 17B: WOLF LAKE EMULSION WITH CS1010

Data for 150 C flow test

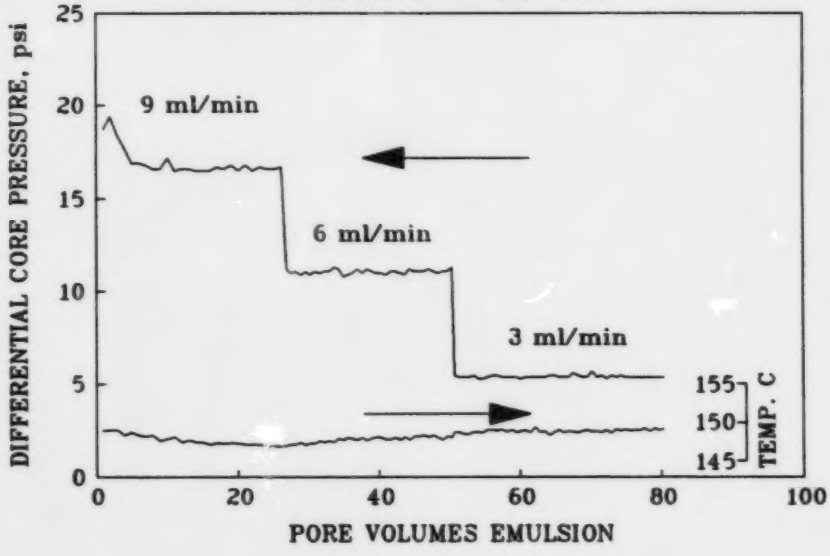


FIG. 17

FIG. 18A: Droplet Size Distribution

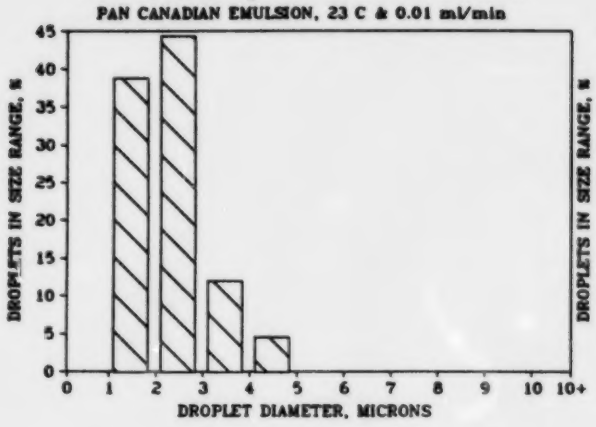
PAN CANADIAN EMULSION, 23 C & 0.01 ml/min
DROPLETS IN SIZE RANGE, %
0 5 10 15 20 25 30 35 40 45
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 18D: Droplet Size Distribution

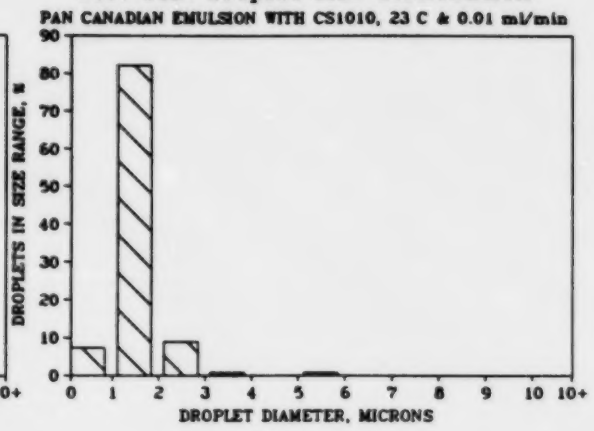
PAN CANADIAN EMULSION WITH CS1010, 23 C & 0.01 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70 80 90
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 18B: Droplet Size Distribution

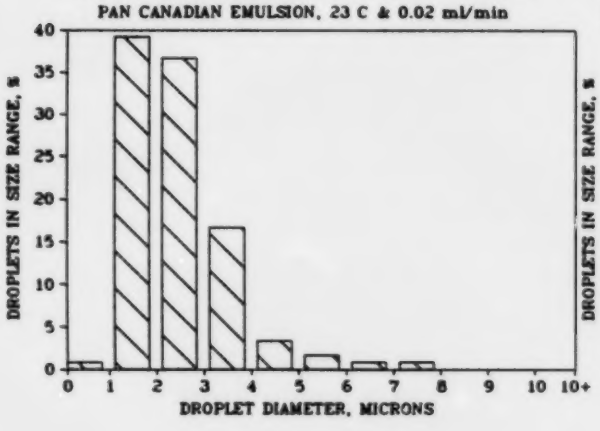
PAN CANADIAN EMULSION, 23 C & 0.02 ml/min
DROPLETS IN SIZE RANGE, %
0 5 10 15 20 25 30 35 40
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 18E: Droplet Size Distribution

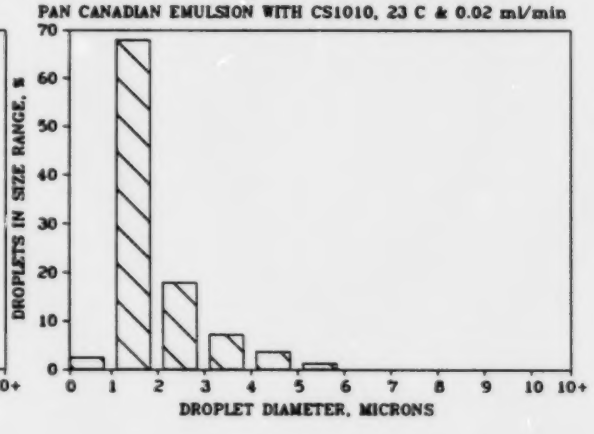
PAN CANADIAN EMULSION WITH CS1010, 23 C & 0.02 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 18C: Droplet Size Distribution

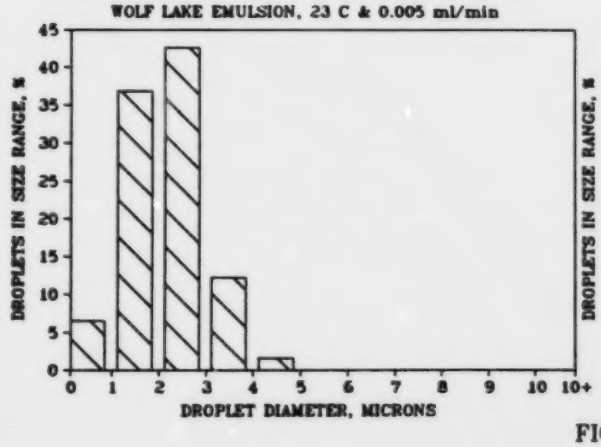
WOLF LAKE EMULSION, 23 C & 0.005 ml/min
DROPLETS IN SIZE RANGE, %
0 5 10 15 20 25 30 35 40 45
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 18F: Droplet Size Distribution

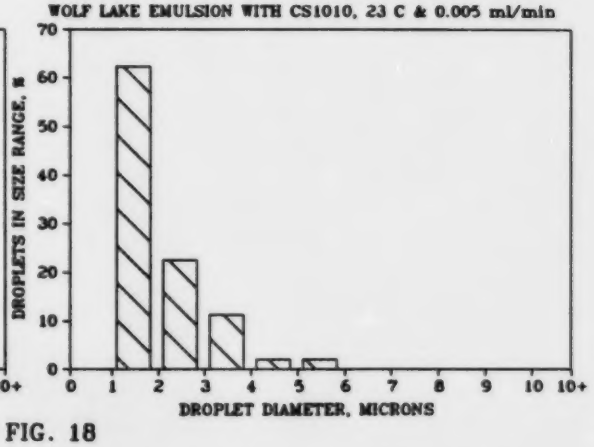
WOLF LAKE EMULSION WITH CS1010, 23 C & 0.005 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 18

FIG. 19A: Droplet Size Distribution

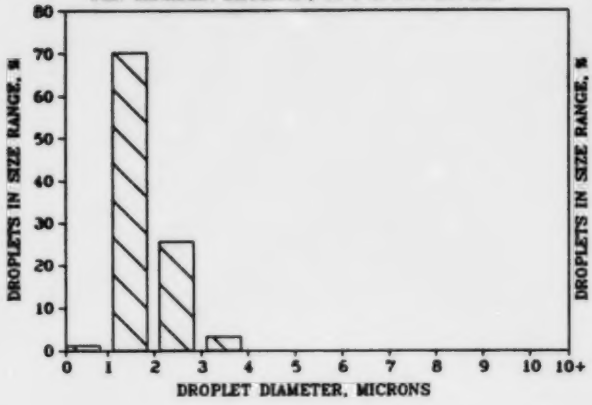
PAN CANADIAN EMULSION, 50 C & 0.05 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70 80
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 19B: Droplet Size Distribution

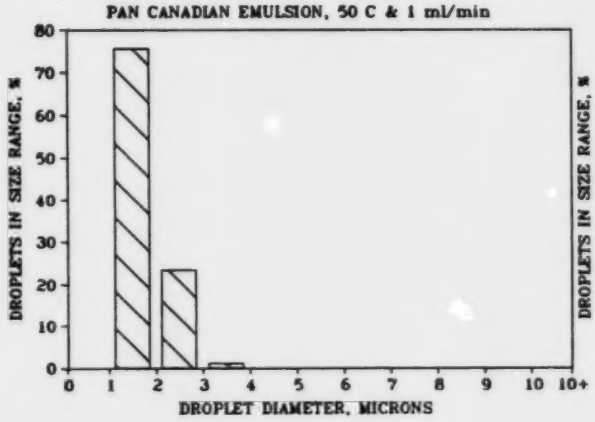
PAN CANADIAN EMULSION, 50 C & 1 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70 80
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 19C: Droplet Size Distribution

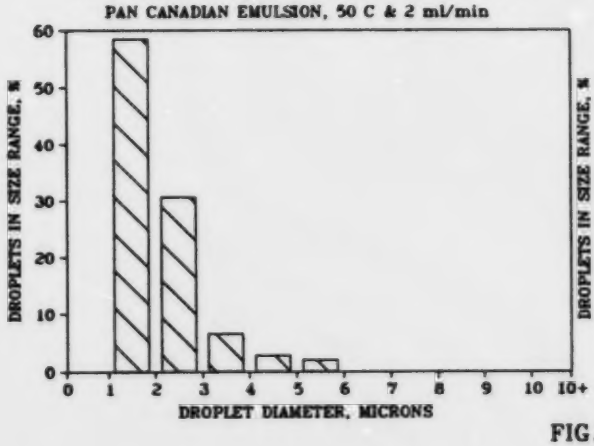


FIG. 19D: Droplet Size Distribution

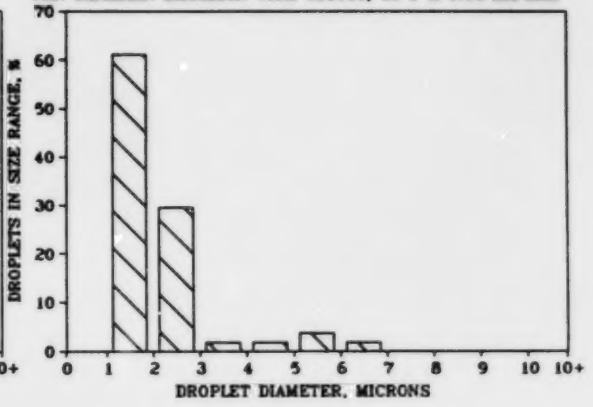
PAN CANADIAN EMULSION WITH CS1010, 50 C & 0.05 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 19E: Droplet Size Distribution

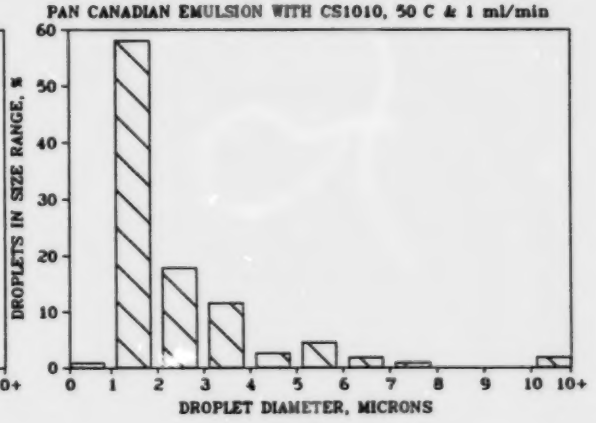
PAN CANADIAN EMULSION WITH CS1010, 50 C & 1 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 19F: Droplet Size Distribution

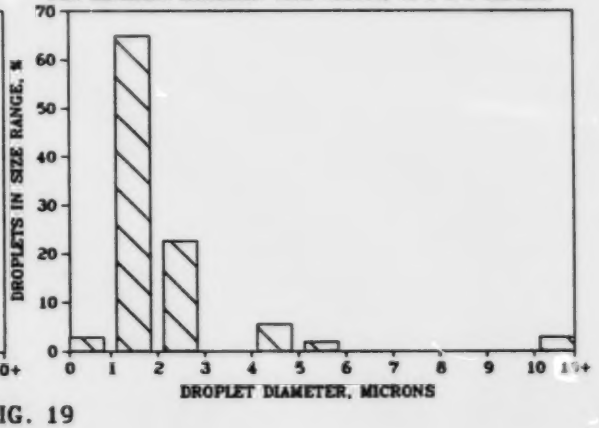
PAN CANADIAN EMULSION WITH CS1010, 50 C & 2 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 19

FIG. 20A: Droplet Size Distribution
PAN CANADIAN EMULSION, 100 C & 0.5 ml/min

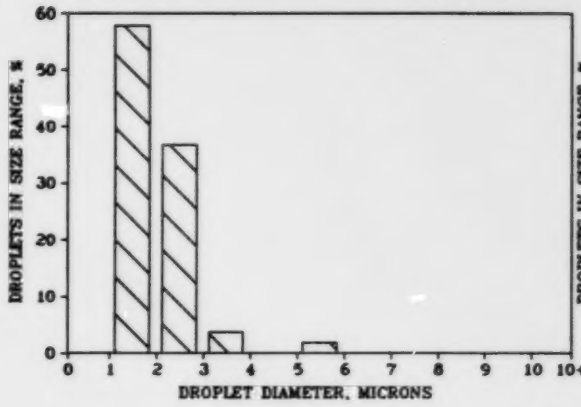


FIG. 20D: Droplet Size Distribution
PAN CANADIAN EMULSION WITH CS1010, 100 C & 0.5 ml/min

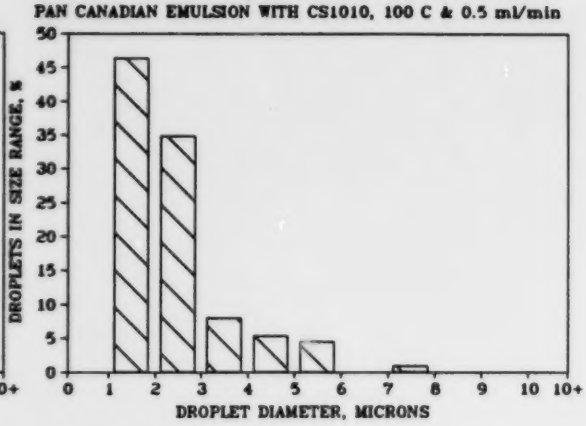


FIG. 20B: Droplet Size Distribution
PAN CANADIAN EMULSION, 100 C & 1 ml/min

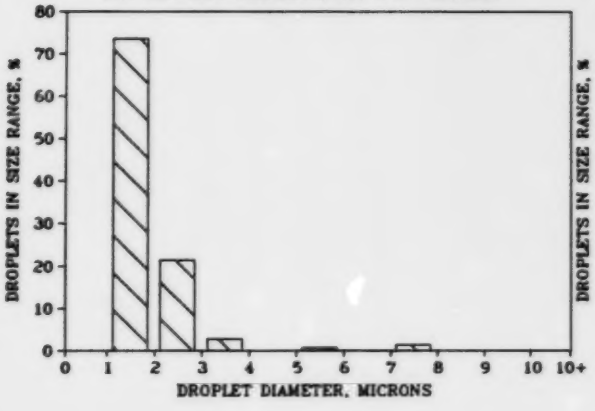


FIG. 20E: Droplet Size Distribution
PAN CANADIAN EMULSION WITH CS1010, 100 C & 1 ml/min

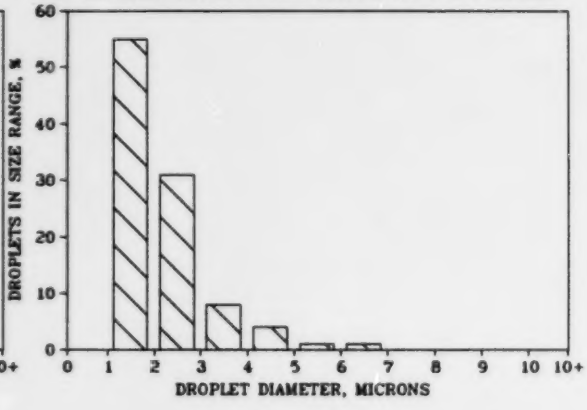


FIG. 20C: Droplet Size Distribution
PAN CANADIAN EMULSION, 100 C & 2 ml/min

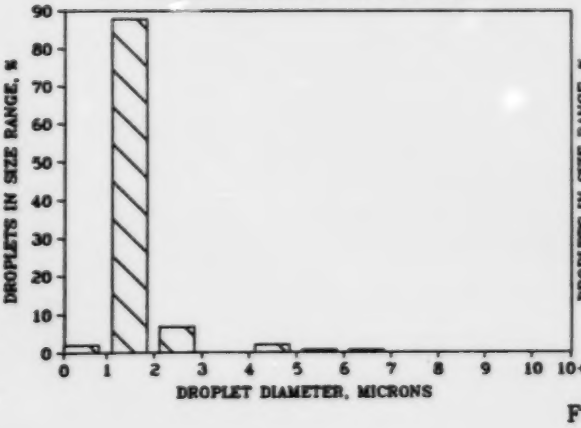


FIG. 20F: Droplet Size Distribution
PAN CANADIAN EMULSION WITH CS1010, 100 C & 2 ml/min

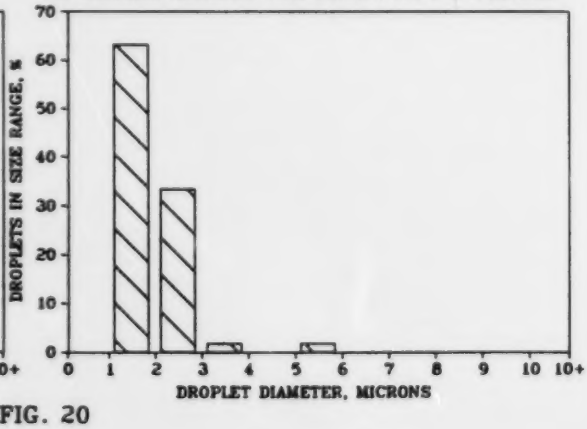


FIG. 20

FIG. 21A: Droplet Size Distribution

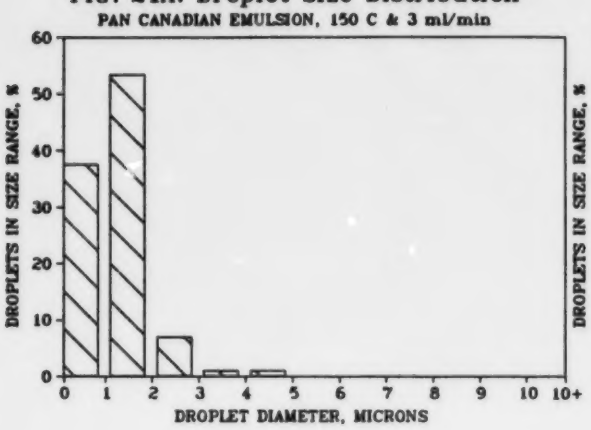


FIG. 21D: Droplet Size Distribution

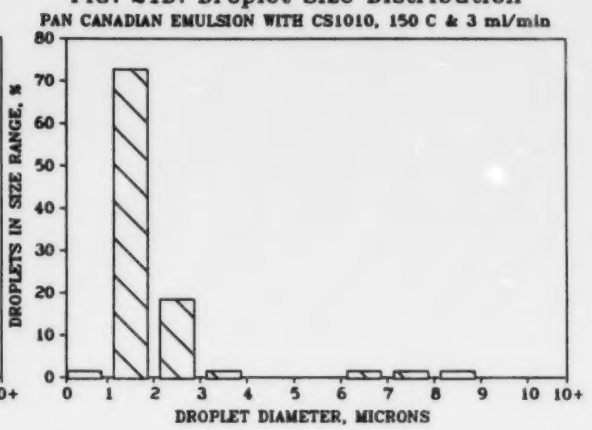


FIG. 21B: Droplet Size Distribution

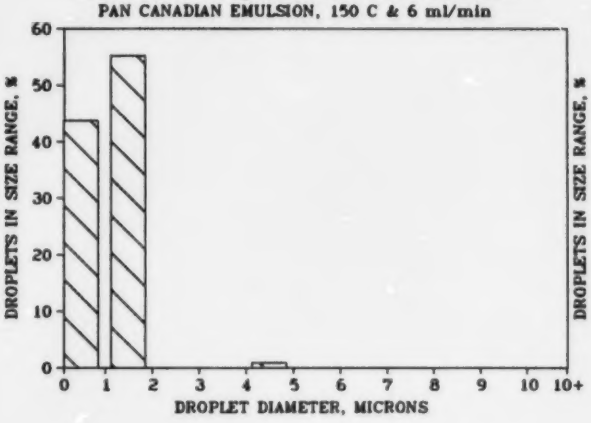


FIG. 21E: Droplet Size Distribution

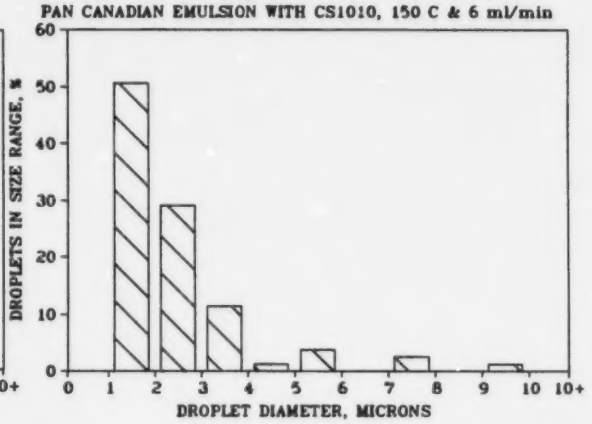


FIG. 21C: Droplet Size Distribution

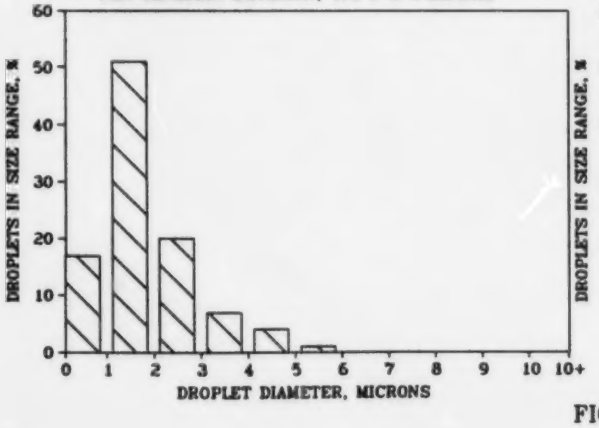


FIG. 21F: Droplet Size Distribution

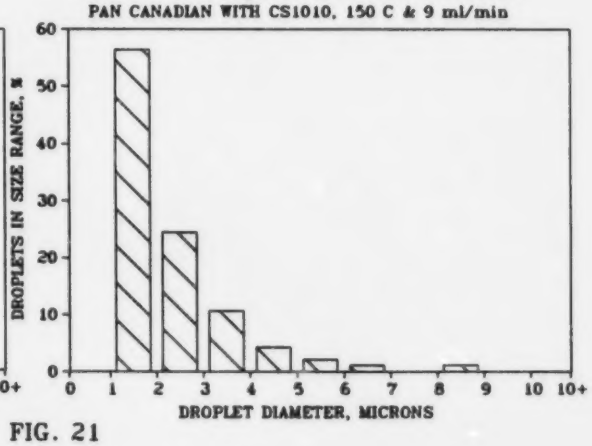


FIG. 21

FIG. 22A: Droplet Size Distribution

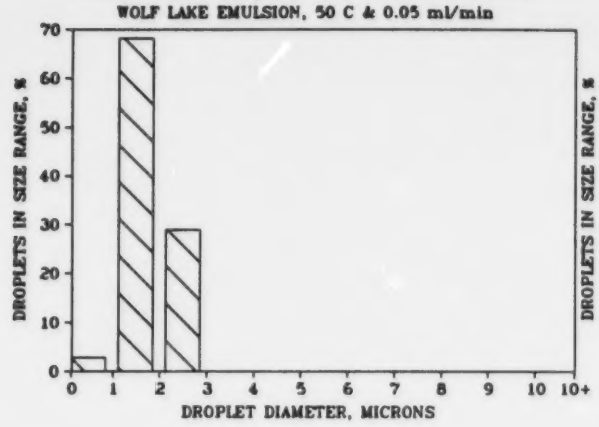


FIG. 22D: Droplet Size Distribution

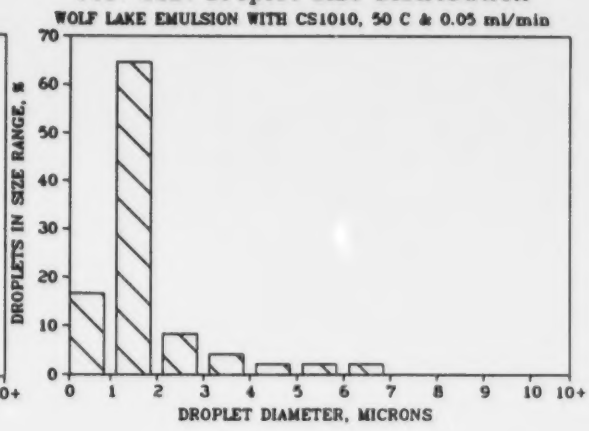
WOLF LAKE EMULSION WITH CS1010, 50 C & 0.05 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 22B: Droplet Size Distribution

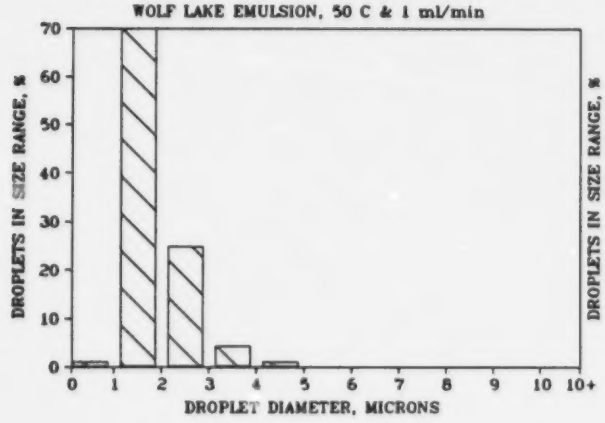


FIG. 22E: Droplet Size Distribution

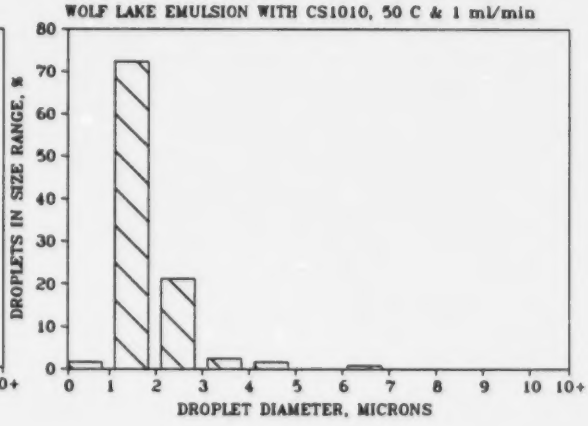
WOLF LAKE EMULSION WITH CS1010, 50 C & 1 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70 80
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 22C: Droplet Size Distribution

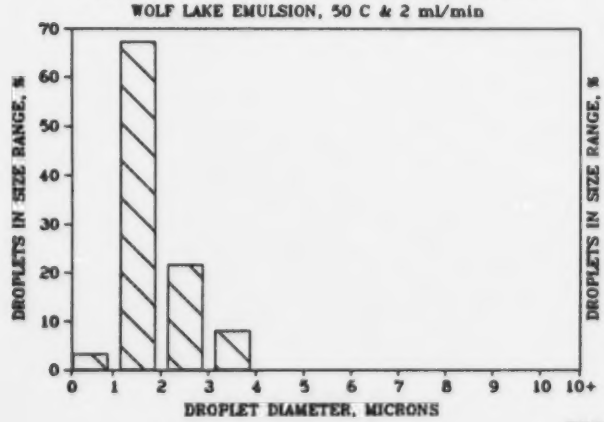


FIG. 22F: Droplet Size Distribution

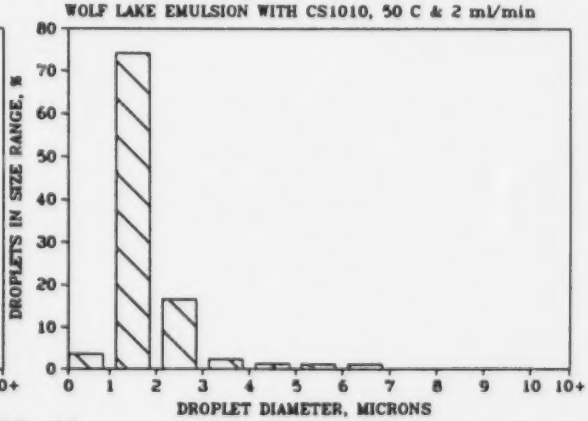
WOLF LAKE EMULSION WITH CS1010, 50 C & 2 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70 80
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 22

FIG. 23A: Droplet Size Distribution

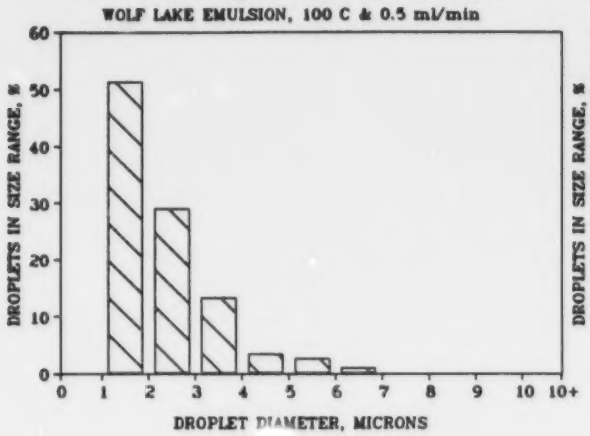


FIG. 23B: Droplet Size Distribution

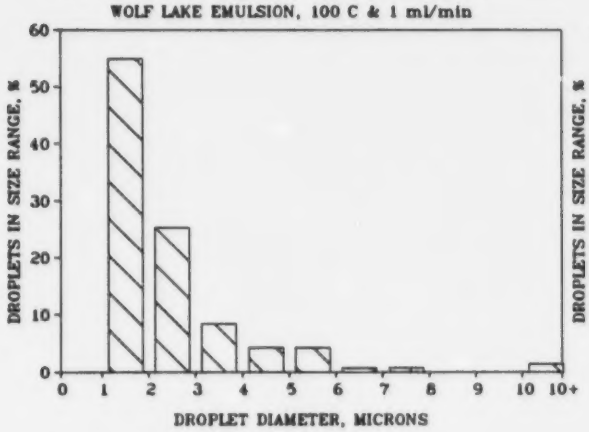


FIG. 23C: Droplet Size Distribution

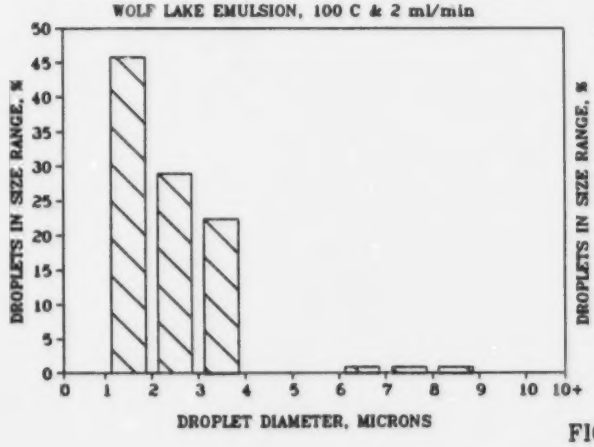
WOLF LAKE EMULSION, 100 C & 2 ml/min
DROPLETS IN SIZE RANGE, %
0 5 10 15 20 25 30 35 40 45 50
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 23D: Droplet Size Distribution

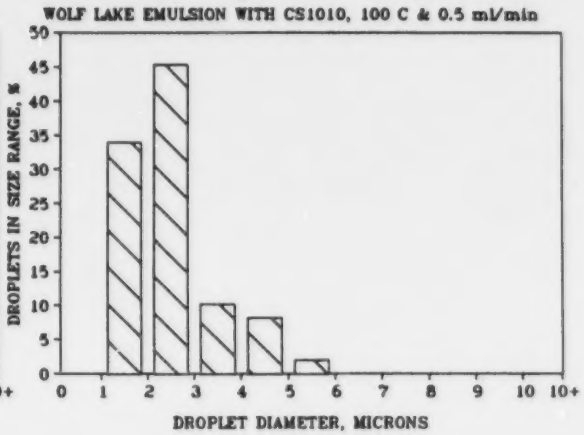
WOLF LAKE EMULSION WITH CS1010, 100 C & 0.5 ml/min
DROPLETS IN SIZE RANGE, %
0 5 10 15 20 25 30 35 40 45 50
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 23E: Droplet Size Distribution

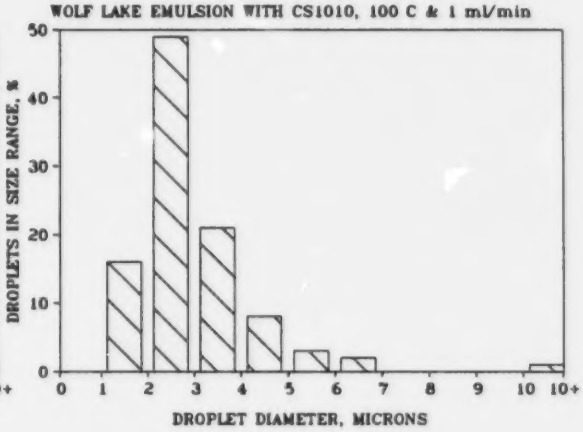
WOLF LAKE EMULSION WITH CS1010, 100 C & 1 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 23F: Droplet Size Distribution

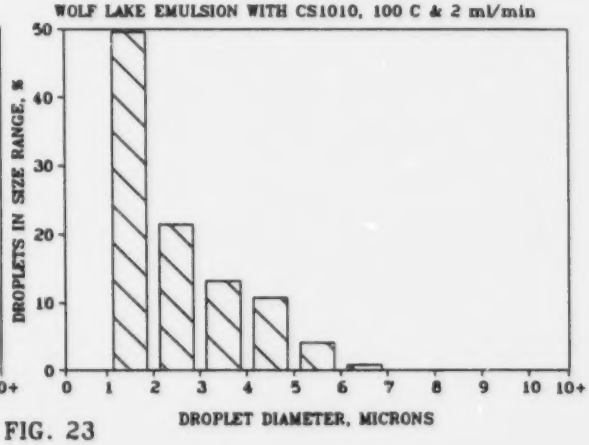
WOLF LAKE EMULSION WITH CS1010, 100 C & 2 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 23

FIG. 24A: Droplet Size Distribution

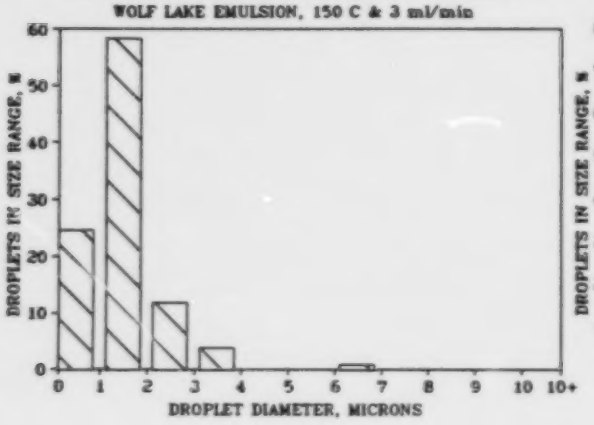


FIG. 24B: Droplet Size Distribution

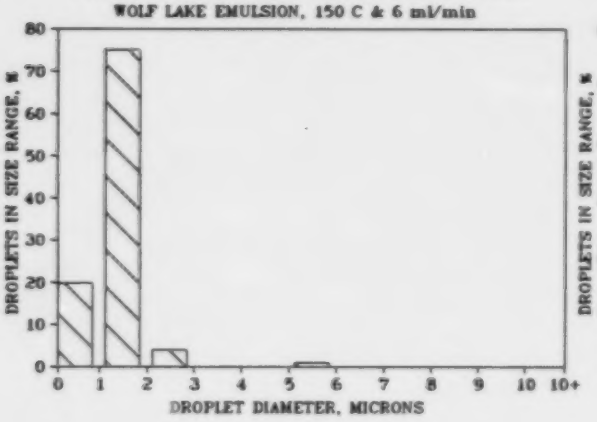


FIG. 24C: Droplet Size Distribution

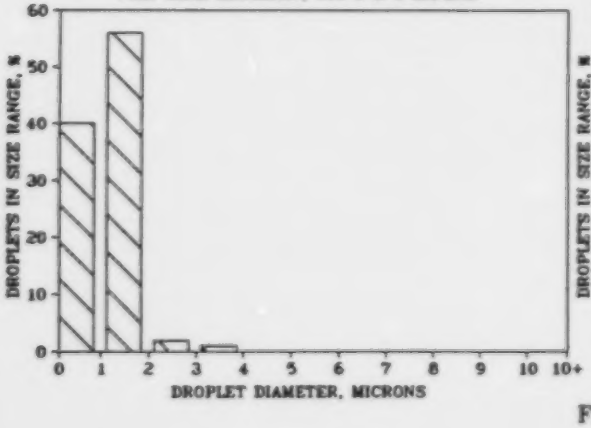


FIG. 24D: Droplet Size Distribution

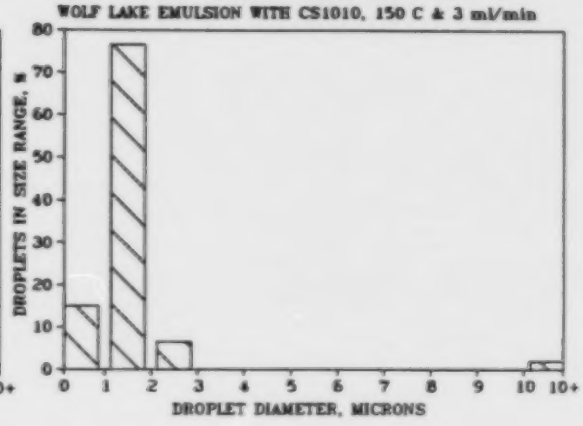
WOLF LAKE EMULSION WITH CS1010, 150 C & 3 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60 70 80
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 24E: Droplet Size Distribution

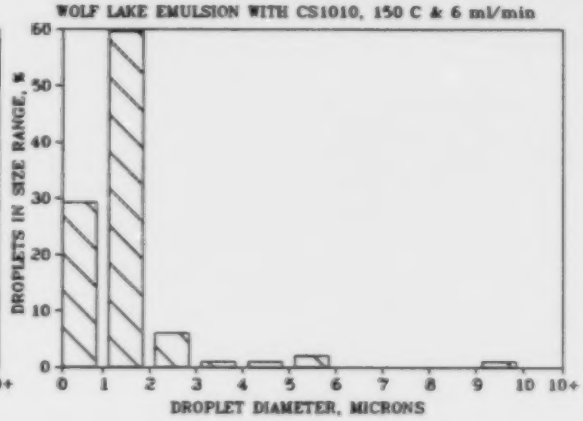
WOLF LAKE EMULSION WITH CS1010, 150 C & 6 ml/min
DROPLETS IN SIZE RANGE, %
0 10 20 30 40 50 60
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 24F: Droplet Size Distribution

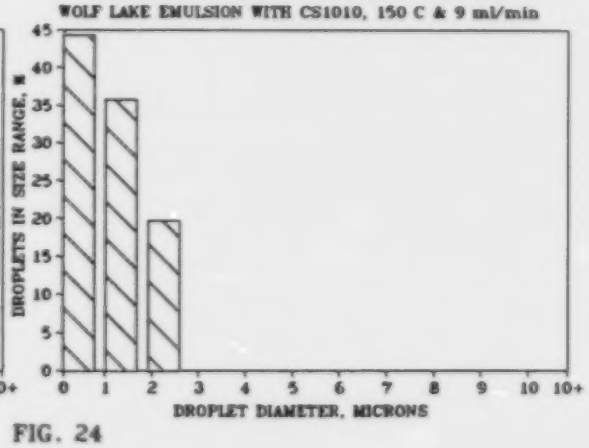
WOLF LAKE EMULSION WITH CS1010, 150 C & 9 ml/min
DROPLETS IN SIZE RANGE, %
0 5 10 15 20 25 30 35 40 45
0 1 2 3 4 5 6 7 8 9 10 10+
DROPLET DIAMETER, MICRONS

FIG. 24

FIG. 25A: PRODUCED EMULSION WATER CONTENT

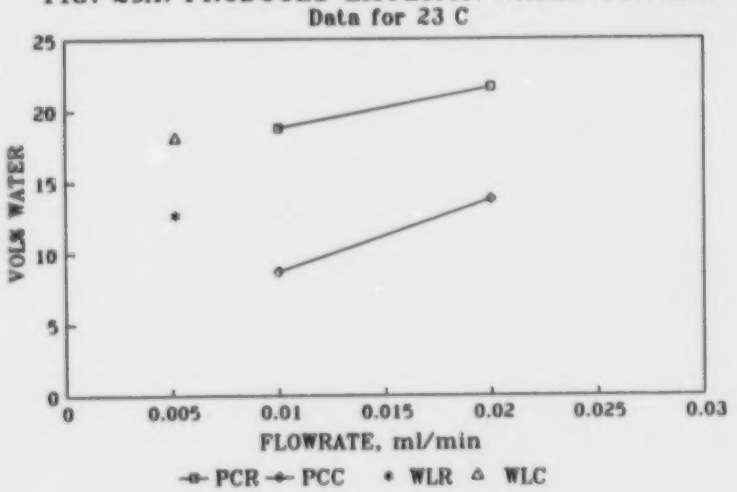


FIG. 25B: PRODUCED EMULSION WATER CONTENT

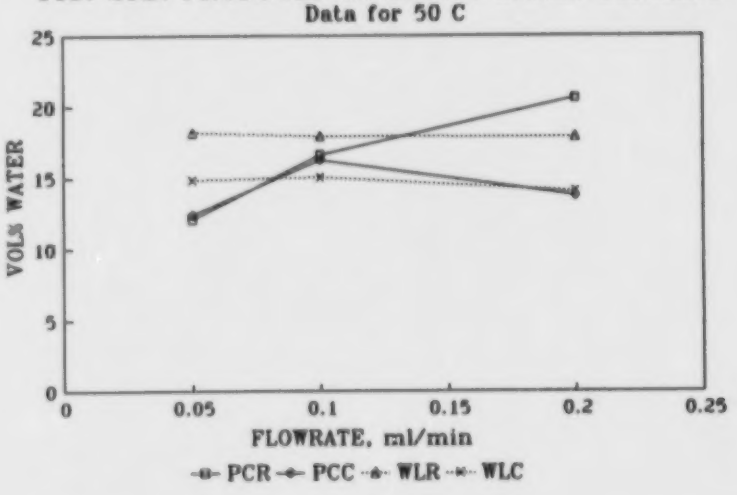


FIG. 25C: PRODUCED EMULSION WATER CONTENT

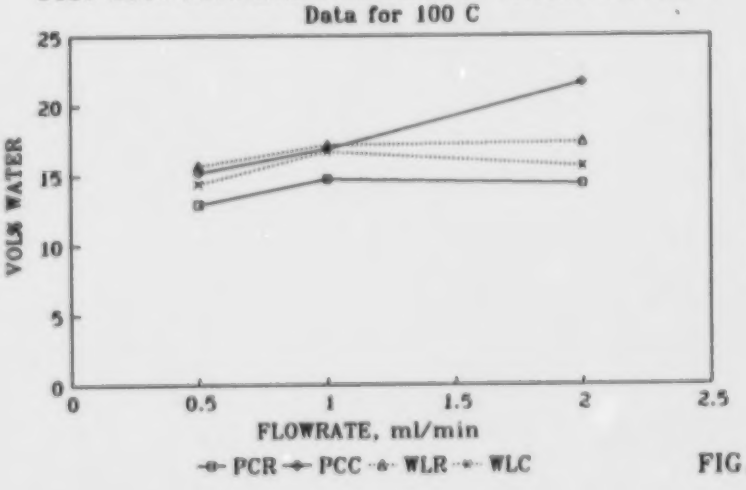


FIG. 25D: PRODUCED EMULSION WATER CONTENT

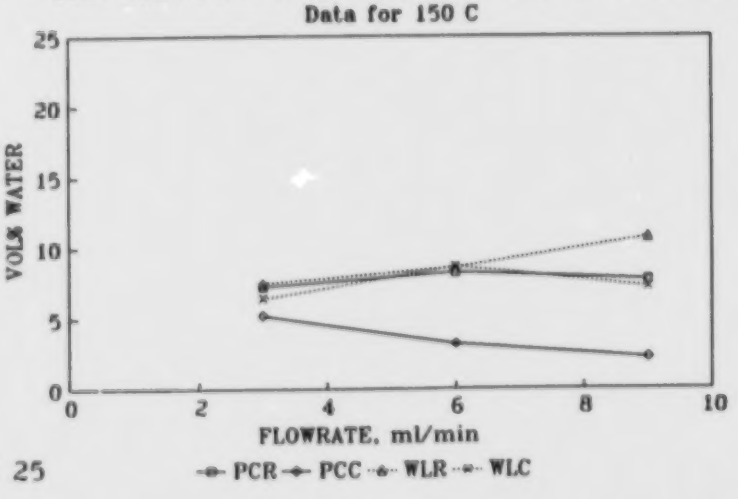


FIG. 25

FIG. 26A: SHEAR STRESS vs. SHEAR RATE

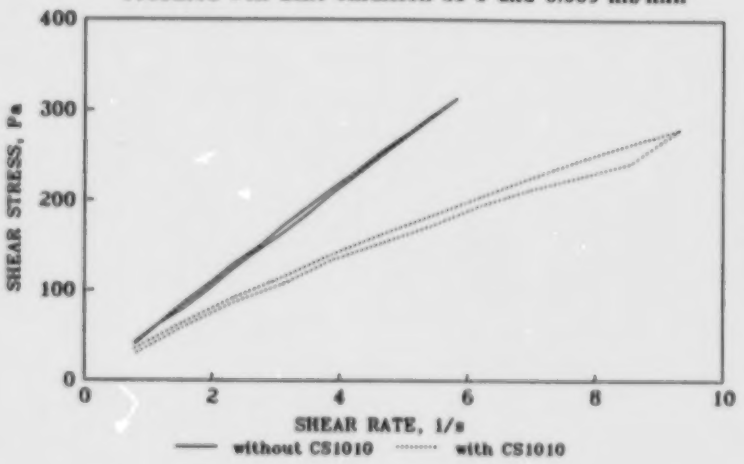


FIG. 26B: SHEAR STRESS vs. SHEAR RATE

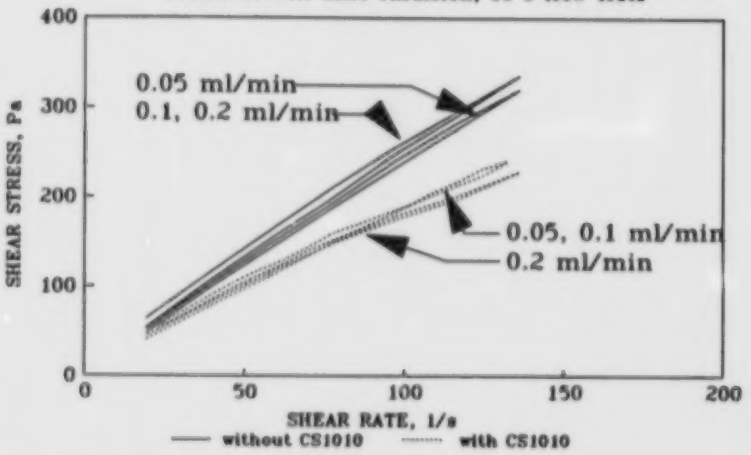


FIG. 26C: SHEAR STRESS vs. SHEAR RATE

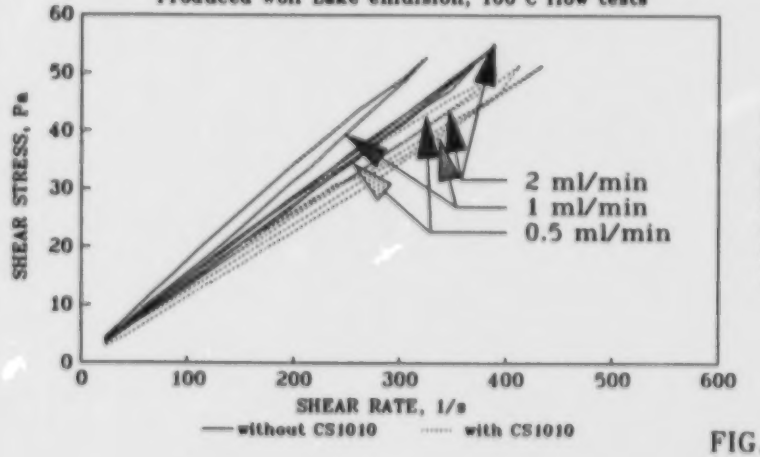


FIG. 26D: SHEAR STRESS vs. SHEAR RATE

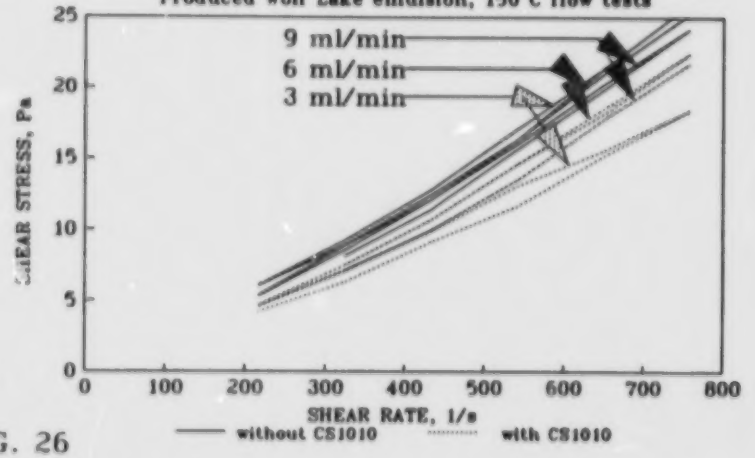


FIG. 26

FIG. 27A: SHEAR STRESS vs. SHEAR RATE

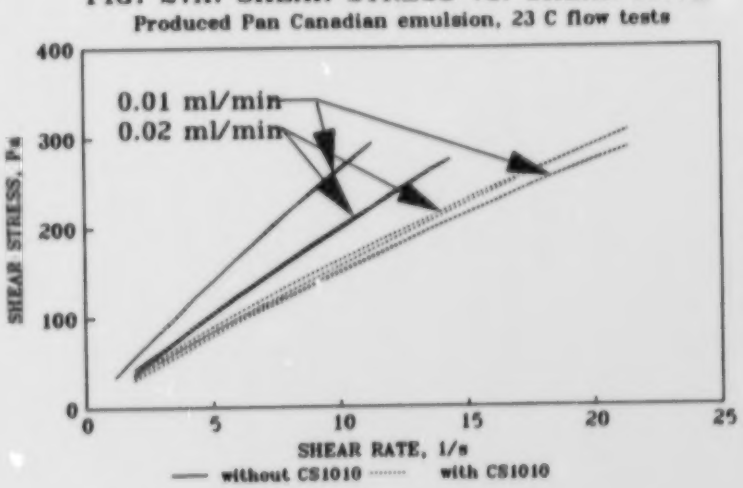


FIG. 27B: SHEAR STRESS vs. SHEAR RATE

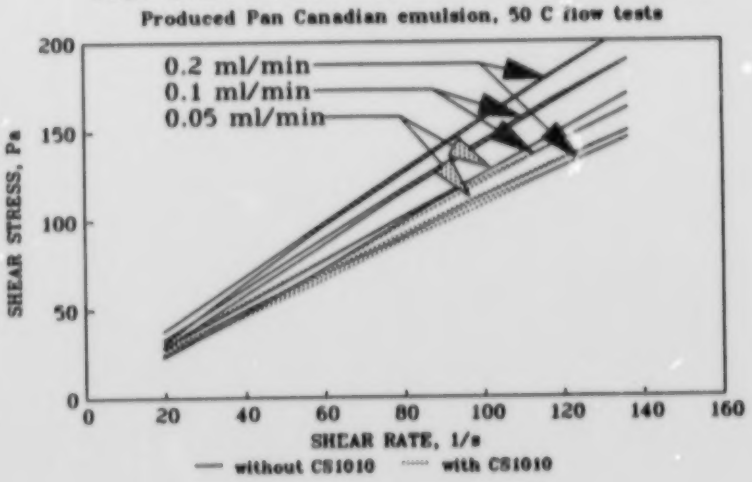


FIG. 27C: SHEAR STRESS vs. SHEAR RATE

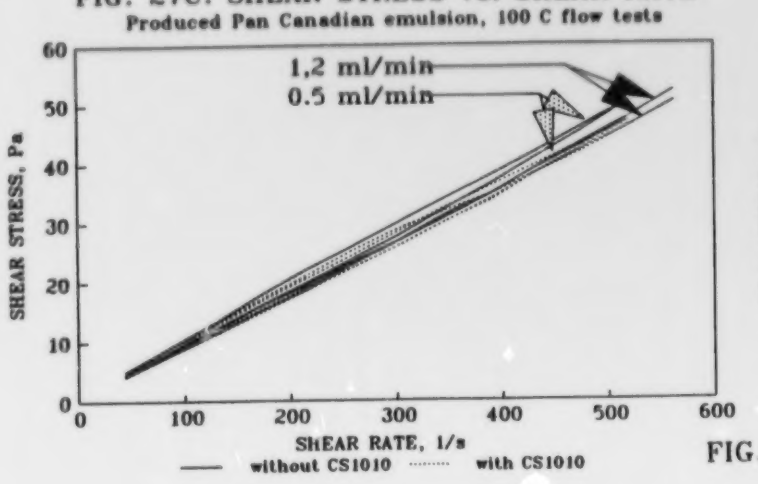


FIG. 27D: SHEAR STRESS vs. SHEAR RATE

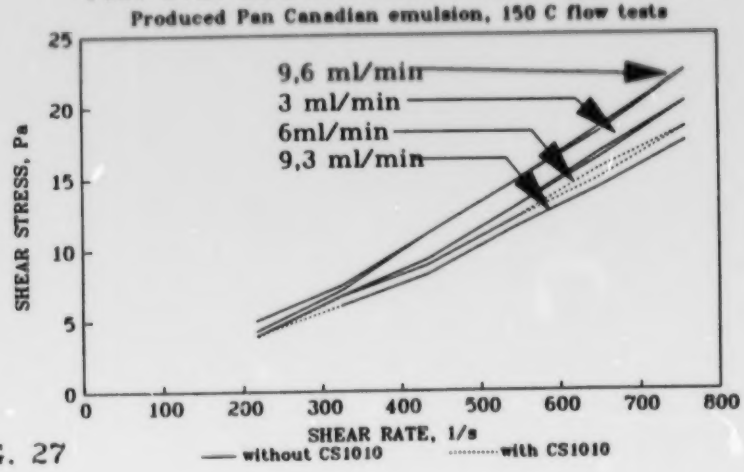


FIG. 27